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SECTORAL TRENDS AND DRIVING FORCES OF GLOBAL ENERGY USE AND GREENHOUSE GAS EMISSIONS

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Abstract. Disaggregation of sectoral energy use and greenhouse gas emissions trends reveals striking differences between sectors and regions of the world. Understanding key driving forces in the energy end-use sectors provides insights for development of projections of future greenhouse gas emissions. This paper examines global and regional historical trends in energy use and carbon emissions in the industrial, buildings, transport, and agriculture sectors. Activity and economic drivers as well as trends in energy and carbon intensity are evaluated. We show that macro-economic indicators, such as GDP, are insufficient for comprehending trends and driving forces at the sectoral level. These indicators need to be supplemented with sector-specific information for a more complete understanding of future energy use and greenhouse gas emissions.

Key words: agriculture energy use, buildings energy use, carbon emissions, energy use, greenhouse gas emissions, industrial energy use, transport energy use

1. Introduction

Future projections of greenhouse gas emissions rely on a number of variables for predicting trends in energy use, including both the level of energy demand and the various sources used to provide this energy. Macro-economic models use historical data as well as estimates of future population, gross domestic product (GDP), autonomous energy efficiency improvement rates, elasticities, and energy prices to determine energy demand levels. These variables, however, do not clearly explain all of the driving forces behind historical or future energy use patterns. As such, more detailed socio-economic and technical information is needed by policy analysts and policymakers. Only with such information can they identify greenhouse gas mitigation measures and formulate policies to implement these measures.

Greenhouse gas emissions from energy use, predominately in the form of carbon emissions, are the result of burning carboniferous fossil fuels. This paper reviews historical trends in energy use and carbon emissions and provides insights on driving forces such as economics, activity levels, and energy and carbon intensity trends. To improve our understanding of global energy use and carbon emissions trends and relationships, we focus on the key sectors of the economy that use energy: industry, buildings, transport, and agriculture. To gain insight on regional trends, we divide the world into four categories based on similar economic development characteristics: industrialized countries, economies in transition in Eastern Europe and the former Soviet Union (EITs), developing countries in Asia/Pacific (DC-AP), and the rest of the world (ROW).[1]

The industrial sector is extremely diverse, encompassing the extraction of natural resources, conversion into raw materials, and manufacture of finished products. Five energy-intensive industrial sub-sectors account for roughly 45% of all industrial energy consumption (iron and steel, chemicals, petroleum refining, pulp and paper,

[1] We recognize that the countries of the EIT region are also industrialized, but have separated them from the other industrialized countries due to their distinct situation as a group of countries undergoing similar economic transitions from centrally-planned economies to market-based economies. A list of the countries included in each region is provided in Appendix A.

and cement). These industries are generally engaged in the transformation of raw material inputs (e.g. iron ore, crude oil, wood) into usable materials and products for an economy. Throughout this paper, we focus on the iron and steel industry when discussing energy-intensive industry.

Energy use in residential and commercial buildings varies throughout the world, reflecting differing climatic conditions, building construction practices, appliance and equipment penetrations, and overall levels of energy demand. Residential buildings range from single-family, detached dwellings to multi-family apartment complexes. Energy consumption levels depend on building shell features such as insulation levels and the energy-efficiency of windows as well as the number of energy-using appliances, how these appliances are used, and their energy-efficiency. Energy use in commercial buildings is also related to features of the building shell and appliance and equipment penetration levels; analysts have shown a strong relationship between commercial building type and energy use.

Transport sector development is easy to quantify; world vehicle stocks, fuel consumption and fuel prices are well known. In addition, there has been considerable modeling in the transport sector, probably because of the high degree of government involvement in transport infrastructure planning. Transport energy use can be disaggregated into passenger and freight transport, and by modes such as automobile, truck, rail, ship, or air. Road transport, both passenger and commercial, accounts for the vast majority of total transport energy use.

Commercial energy is used in the agriculture sector for equipment, irrigation, drying, horticulture, and raising livestock. Energy use for production of fertilizers and pesticides is not included in this sector bur rather is accounted for in the industrial sector. Non-commercial energy, an important element of traditional agriculture, is also not included in this discussion. Due to a lack of detailed information on this sector, we do not include it in our discussion of sectoral driving forces.

The goal of this paper is to provide historical sectoral-level energy and carbon emissions data as well as an understanding of the key underlying drivers of energy use and carbon emissions in each sector. Such information is helpful for the development of energy use and carbon emissions scenarios because it provides modelers with a historical basis from which to extrapolate trends as well as information on how various factors such as population, energy intensity, and structural trends affect energy use and associated greenhouse gas emissions.

We first discuss historical trends in energy use and greenhouse gas emissions by end-use sector for four world regions. After that, we examine activity and economic drivers of energy use and greenhouse gas emissions in the industrial, buildings, and transport sector. Next we discuss energy and carbon intensity trends by sector. We conclude by commenting on how these historical trends and drivers can be used in the development of greenhouse gas emissions scenarios.

2. Data and Methodology

2.1 DATA

This paper presents energy use and carbon emissions data for the industrial, buildings (both commercial and residential), transport, and agriculture sectors. The end-use breakdown was made using IEA (International Energy Agency) statistics (IEA, 1997a; IEA 1997b; IEA, 1997c), British Petroleum (BP) data for energy trends in the EIT region (BP, 1997), and expert judgment of the authors.[2] The IEA statistics, on which most of the data in this paper are based, include all "commercial" sources of energy, defined as hard coal, brown coal/lignite, natural gas, crude oil, natural gas liquids, hydro, geothermal/solar, wind, tide, and nuclear power as well as coal products, manufactured gases, petroleum products and electricity. Data on biomass ("combustible renewable and waste") energy sources are included, although there are uncertainties regarding the quality of these data (IEA, 1994a; IEA, 1997a; IEA 1997b). IEA data are available beginning in 1960 for industrialized countries and

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[2] The authors worked with a number of staff members at the IEA to both understand the IEA end-use sector allocations and to use their knowledge to assist in the reallocation described in section 2.2.

beginning in 1971 for all other countries. Primary energy was calculated assuming an electricity generation efficiency of 33%. Following IEA convention, we do not include the energy used for conversion of primary fuels in the end-use sector totals. If petroleum refining and coke oven gas were added to the industrial sector values, global industrial sector energy use would increase by roughly 12%.

The energy use and carbon emissions data presented in this paper are based on a reallocation of IEA end-use data for all regions except the EIT region. The IEA energy statistics report final energy and electricity use for end-use sectors defined as industry (TOTIND), transport (TOTTRANS), and other (TOTOTHER). The other category is further divided into agriculture (AGRICULT), commercial and public services (COMMPUB), residential (RESIDENT), and non-specified other (ONONSPEC). This last category includes energy use in the agriculture, commercial and public services, and residential sectors that has not been allocated to these end-use sectors by the submitting countries. In some cases, there is no entry for the non-specific other category, indicating that all end-use energy consumption has been allocated to the other end-use sectors. However, some countries require the reallocation of the non-specified other category to the end-use sectors. This is especially important for those years in which a particular country reports all of the other energy use as non-specified. To perform this reallocation, the non-specified other category was allocated to the other end-use sectors (agriculture, commercial and public services, residential) based on the share of allocated energy in each of these sub-sectors for each of the industrialized countries and the IEA groupings of Asia excluding Japan, Africa, Latin America, and the Middle East.[3]

Carbon embodied in electricity and heat consumption was calculated by multiplying the amount of electricity and heat used by average yearly carbon factors for electricity and heat produced. Carbon factors were derived as the ratio of carbon emissions from all fuel inputs at power plants to electricity or heat delivered.[4] Fuel inputs for electricity production were separated from inputs to heat production. Fuel inputs to electricity production contain fuels that are used in electricity plants (both public and autoproducer plants) and fuels that are used for electricity production in combined heat and power plants. Fuel inputs into heat production combine fuels used in heat plants (both public and autoproducer plants) and fuels that are used for heat production in combined heat and power plants.[5] Fuel inputs in combined heat and power plants are separated into fuel inputs for electricity and heat production according to the shares of electricity and heat produced in these plants. The data for fuel inputs in all power plants, as well as for electricity and heat output from each type of plant, were taken from the IEA Extended Energy Balances Database. The fuel inputs were multiplied by the respective carbon emission factors for each fuel. We calculated carbon emissions by sector for industrialized countries and selected EIT, DC-AP, and ROW countries. When aggregated, our total carbon emissions for a country or region differ from IEA values because we only include emissions from fuel combustion, electricity, and heat consumption. IEA CO_2 statistics include a number of other categories, such as unallocated non-energy use, that we did not include.

We used BP data for energy use trends in the EIT region because IEA data show growth in buildings sector energy use between 1990 and 1995 in this region, despite the serious economic difficulties experienced during this period. In contrast, BP statistics show a decline in overall buildings energy use at this time. EIT data were provided in primary units by BP. We converted these primary values to fuel and electricity values based on their shares as reported in IEA statistics for this region. Sectoral energy use shares were calculated based on a previous analysis (WEC, 1995a). Carbon emissions for the former Soviet Union were carefully derived following a fuel-by-fuel review of IEA data that included reallocations to attempt to correct for missing or obviously erroneous data. Carbon emissions for the other EIT countries included in Table 4 were calculated using IEA data. We strongly caution the reader to recognize the uncertainty in the values presented for this

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[3] The results of this allocation scheme were compared to LBNL sectoral energy data for a number of industrialized countries. In general, the sectoral energy consumption values based on allocated IEA data compared favorably to LBNL data for total buildings and agriculture for most countries. Larger discrepancies were seen between the LBNL data and the allocated IEA data at the level of commercial and residential buildings. Further analysis of the differences between the allocated IEA data and LBNL data is required to fully understand energy use trends at the commercial and residential buildings level.

[4] Delivered electricity or heat is primary (gross) electricity or heat produced excluding distribution losses.

[5] This excludes heat pumps and electric boilers since fuel inputs for those energy producers are electricity and heat, respectively.

region; however, we believe that these are the best sectoral level estimates of energy use and carbon emissions currently available for the EIT countries.

Additional difficulties were encountered with the data for China for 1971 and 1975, years for which official data are scarce for that country. For final energy, the reported values for industry for these years (0.96 and 1.3 EJ, respectively) represented significantly lower shares of total final energy (12% and 13%, respectively) than the 61% to 66% shares seen in 1980-1995. Thus, total industry values for 1971 and 1975 were adjusted to 60% of total final energy for 1971 and 1975. Similar adjustments were made in the transport sector, where the 1971 and 1975 values were 3% and 4% of total final energy, respectively. These values were adjusted to be 6% of total final energy which is more closely aligned with the 8 to 9% experienced in later years. No values were reported for the categories of agriculture, commercial buildings, and residential buildings for China for 1971 and 1975 (except residential in 1975). A non-specified other value was reported for both of these years. However, adding the non-specified other (plus residential in 1975), industry, and transport values does not result in the reported total final consumption value for these sectors. To resolve this discrepancy, the reported values for non-specified other for 1971 and 1975 were not used; instead non-specified other was calculated as the difference between the adjusted industry and transport values and total final consumption. This non-specified other category was then allocated to agriculture, commercial buildings, and residential buildings based on the 1980 shares of these end-use sectors. Similar adjustments and reallocations were made to the electricity values for 1971 and 1975 for China.

We compared the IEA data for China to Chinese national statistics for the years 1980 to 1990 (Sinton, 1996). Final energy use was virtually the same in all sectors for all years, except for the residential sector in 1990 (national statistics were 1.4 EJ higher than IEA statistics) and the industrial sector for all three years (national statistics were 2.6 EJ, 3.4 EJ, and 5.1 EJ higher that IEA statistics in 1980, 1985, and 1990, respectively). We use IEA statistics in this paper, but caution the reader that more research is needed to understand the differences between IEA statistics and Chinese national statistics.

2.2 Methodology

This paper presents historical energy use and carbon emissions trends and discusses the underlying drivers of these trends. The main factors affecting growth of carbon emissions in an economy include the rate of population growth, the size and structure of the economy (depending on consumption patterns and stage of development), the amount of energy consumed per unit of activity, and the specific carbon emissions of the fuel mix used. Our discussion of the drivers is guided by the terms of the so-called Kaya identity (Kaya, 1989) as outlined by equation 1.

$$\text{CO}_2\ \text{Emissions} = \text{Population} \times \frac{\text{GDP}}{\text{Person}} \times \frac{\text{Energy}}{\text{GDP}} \times \frac{\text{CO}_2}{\text{Energy}} \qquad (1)$$

We have redefined the terms slightly to more closely match the available data and the characteristics of the end-use sectors that we focus on in this paper. Thus, our discussion is structured as given by equation 2.

$$\begin{array}{c} \text{CO}_2 \\ \text{Emission} \end{array} = \begin{array}{c} \text{Activity} \\ \text{Drivers} \end{array} \times \begin{array}{c} \text{Economic} \\ \text{Drivers} \end{array} \times \begin{array}{c} \text{Energy} \\ \text{Intensity} \end{array} \times \begin{array}{c} \text{Carbon} \\ \text{Intensity} \end{array} \qquad (2)$$

The various terms are defined differently in each end-use sector. For example, while activity is generally linked to population in all sectors, it also includes commodity production levels in the industrial sector, number of persons per household in the residential sector, cubic meters of building space in the commercial sector, and number of vehicles in the transport sector.

We begin with a discussion of historical energy use and carbon emissions trends in Section 3. This is followed in Section 4 with a more detailed discussion of the energy use and carbon emissions drivers and terms in equation 2. We discuss the main drivers for each sector and explain trends and regional variations. Understanding these factors enables calibration of models to trends observed in the past.

3. Historical Trends in Energy Use and Carbon Emissions

3.1 PRIMARY ENERGY DEMAND

Global primary energy use grew from 191 EJ in 1971 to 307 EJ in 1990 at an average annual growth rate (AAGR) of 2.5% per year. This growth tapered off in all sectors after 1990, with total global primary energy increasing to only 319 EJ by 1995 (see Table 1), mainly due to the large declines experienced in the EIT region because of the political and economic restructuring in many of those countries.

Figure 1 shows that the industrial sector clearly dominates total primary energy use, followed by the buildings sector (commercial and residential buildings combined), the transport sector, and the agriculture sector. Figure 2 shows that between 1971 and 1990, the largest annual growth was experienced in the commercial buildings and agriculture sectors. After 1990, these trends shifted, with transport experiencing the fastest growth, while very little growth was seen in the industrial sector. Industrialized countries consumed about 160 EJ (52%) in 1990 compared to 74 EJ (24%) in the EIT, 45 EJ (14%) in the DC-AP, and 30 EJ (10%) in the ROW regions. Growth in primary energy use between 1971 and 1990 was highest in the DC-AP and ROW regions, which grew at average annual rates of 5.8% and 5.4%, respectively. Table 2 provides detailed information on primary energy use by sector by region.

Table 1. Global Primary Energy Use by Sector, 1971-1995 (EJ). Reference: IEA, 1997a; IEA, 1997b; BP, 1997.

	1971	1975	1980	1985	1990	1995	AAGR 1971-90	AAGR 1990-95
Industrial	88.0	98.5	113.5	119.8	129.4	130.8	2.1%	0.2%
Buildings	61.5	70.3	81.3	92.6	105.6	109.8	2.9%	0.8%
Residential	41.7	47.1	54.5	60.6	67.4	69.4	2.6%	0.6%
Commercial	19.8	23.2	26.8	31.9	38.2	40.3	3.5%	1.1%
Transport	37.5	43.6	50.1	54.4	63.3	69.0	2.8%	1.7%
Agriculture	4.4	5.1	6.1	7.5	8.9	9.3	3.8%	0.8%
Total 4 sectors	191.4	217.5	251.0	274.2	307.2	318.8	2.5%	0.7%

Figure 1. Global Primary Energy Use by Sector, 1971 to 1995.

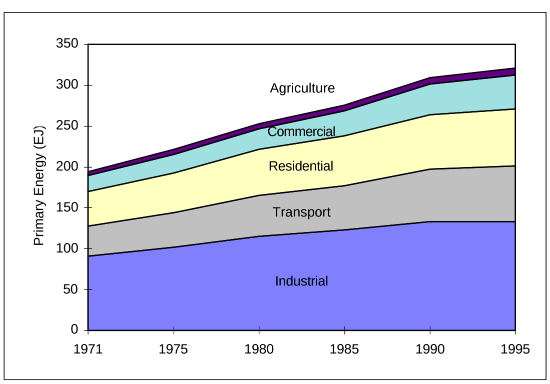
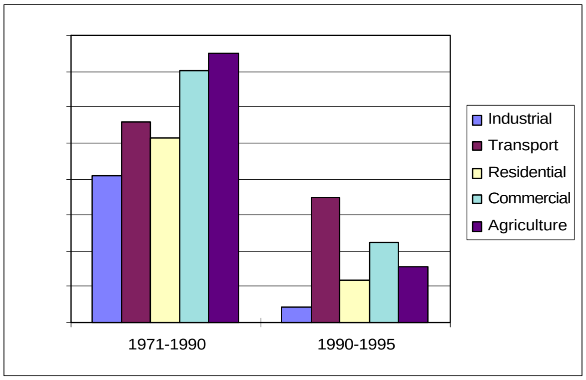


Figure 2. Average Annual Growth in Global Primary Energy Use by Sector.



3.1.1 Primary Energy Demand: Industry

In 1990, industry accounted for 42% (129 EJ) of global energy use. Between 1971 and 1990, industrial energy use grew at a rate of 2.1% per year, slightly less than the world total energy demand growth of 2.5% per year. This growth rate has slowed in recent years, and was virtually flat between 1990 and 1995, primarily because of declines in industrial output in the EIT region. Energy use in the industrial sector is dominated by the industrialized countries, which accounted for 42% of world industrial energy use in 1990. Countries in the EIT, DC-AP, and ROW regions used 29%, 20%, and 9% of world industrial energy use, respectively, that year (see Table 2).

Industrial energy consumption in the industrialized countries increased at an average rate of 0.6% per year between 1971 and 1990, from 49 EJ to 54 EJ. The share of industrial sector energy consumption within the industrialized countries declined from 40% in 1971 to 33% in 1995. This decline partly reflects the transition toward a less energy-intensive manufacturing base, as well as the continued growth in transportation demand, resulting in large part from the rising importance of personal mobility in passenger transport use. The industrial sector dominates in the EIT, accounting for more than 50% of total primary energy demand, the result of the long-term policy emphasizing materials production that was promoted under years of central planning. Average annual growth in industrial energy use in this region was 2.0% between 1971 and 1990 (from 26 EJ to 38 EJ), but dropped by an average of –7.3% per year between 1990 and 1995.

Table 2. Primary Energy Use by Sector and Region, 1971-1995 (EJ).
Reference: IEA, 1997a; IEA, 1997b; BP, 1997.

	1960	1971	1975	1980	1985	1990	1995	AAGR 1960-1990	AAGR 1971-1990	AAGR 1990-1995
Industrial Sector										
Industrialized Countries	27.7	48.6	49.3	55.0	52.3	54.3	56.8	2.3%	0.6%	0.9%
Economies in Transition		26.0	31.6	34.0	36.9	38.0	26.0		2.0%	-7.3%
Dev. Cos. in Asia-Pacific		8.8	11.5	15.5	20.0	26.1	34.8		5.9%	5.9%
Rest of World		4.6	6.2	8.9	10.5	11.0	13.0		4.7%	3.5%
World		88.0	98.5	113.5	119.8	129.4	130.8		2.1%	0.2%
Buildings Sector										
Industrialized Countries	28.3	44.4	48.9	52.3	56.8	62.3	68.5	2.7%	1.8%	1.9%
Residential	*16.6*	*28.3*	*30.5*	*33.0*	*34.6*	*36.7*	*40.6*	*2.7%*	*1.4%*	*2.0%*
Commercial	*11.7*	*16.1*	*18.4*	*19.3*	*22.2*	*25.6*	*27.9*	*2.6%*	*2.5%*	*1.7%*

Economies in Transition		10.7	13.0	18.2	21.0	23.0	16.2		4.1%	-6.8%
Residential		*8.1*	*9.8*	*12.9*	*14.3*	*15.1*	*10.4*		*3.3%*	*-7.2%*
Commercial		*2.6*	*3.2*	*5.3*	*6.7*	*7.9*	*5.8*		*6.0%*	*-6.1%*
Dev. Cos. in Asia-Pacific		3.6	4.6	5.6	7.9	10.2	12.9		5.7%	4.8%
Residential		*3.0*	*3.9*	*4.6*	*6.3*	*7.9*	*9.3*		*5.2%*	*3.4%*
Commercial		*0.6*	*0.8*	*1.0*	*1.6*	*2.3*	*3.6*		*7.8%*	*8.9%*
Rest of World		2.7	3.7	5.1	6.9	10.1	12.1		7.1%	3.8%
Residential		*2.2*	*2.8*	*3.9*	*5.4*	*7.8*	*9.1*		*6.8%*	*3.2%*
Commercial		*0.5*	*0.8*	*1.2*	*1.5*	*2.3*	*3.0*		*8.5%*	*5.7%*
World		61.5	70.3	81.3	92.6	105.6	109.8		2.9%	0.8%
Residential		*41.7*	*47.1*	*54.5*	*60.6*	*67.4*	*69.4*		*2.6%*	*0.6%*
Commercial		*19.8*	*23.2*	*26.8*	*31.9*	*38.2*	*40.3*		*3.5%*	*1.1%*
Transport Sector										
Industrialized Countries	14.7	26.2	29.4	32.5	33.8	39.4	43.3	3.3%	2.2%	1.9%
Economies in Transition		6.0	7.3	8.0	9.2	10.0	7.3		2.7%	-6.0%
Dev. Cos. in Asia-Pacific		2.0	2.4	3.3	4.3	6.0	8.7		5.9%	7.6%
Rest of World		3.3	4.6	6.3	7.2	7.8	9.6		4.6%	4.2%
World		37.5	43.6	50.1	54.4	63.3	69.0		2.8%	1.7%
Agriculture Sector										
Industrialized Countries	1.2	1.8	1.8	2.1	2.6	2.7	3.0	2.9%	2.2%	1.6%
Economies in Transition		1.3	1.6	1.8	2.4	3.0	1.7		4.5%	-10.6%
Dev. Cos. in Asia-Pacific		0.9	1.3	1.6	1.7	2.3	3.0		4.8%	5.6%
Rest of World		0.4	0.5	0.7	0.8	0.9	1.6		4.7%	12.6%
World		4.4	5.1	6.1	7.5	8.9	9.3		3.8%	0.8%
All Sectors										
Industrialized Countries	71.8	121.0	129.3	141.8	145.5	158.8	171.7	2.7%	1.4%	1.6%
Economies in Transition		44.0	53.5	62.0	69.5	74.0	51.3		2.8%	-7.1%
Dev. Cos. in Asia-Pacific		15.4	19.7	26.0	33.9	44.7	59.5		5.8%	5.9%
Rest of World		11.0	14.9	21.1	25.4	29.8	36.4		5.4%	4.1%
World		191.4	217.5	251.0	274.2	307.2	318.8		2.5%	0.7%

In the DC-AP region, the industrial sector accounted for between 57% and 60% of primary energy consumption during the period 1971 to 1995. Industrial energy use grew rapidly between 1971 and 1995, with an annual average growth rate of 5.9%, jumping from 9 EJ to 35 EJ. The fastest growth in this sector was seen in China and in other rapidly-developing Asian countries. Growth in the ROW region was slightly lower, averaging 4.7% per year between 1971 and 1990 and 3.5% per year between 1990 and 1995. The nature and evolution of the industrial sector varies considerably among developing countries. Some economies that are experiencing continued expansion in energy-intensive industry, such as China and India, show relatively unchanging shares of industrial energy use. In other countries, such as Thailand and Mexico, the share and/or growth of the transportation sector dominate. Many smaller countries have remained primarily agrarian societies with modest manufacturing infrastructure.

3.1.2 Primary Energy Demand: Buildings

In 1990, residential and commercial buildings consumed slightly over 100 EJ of primary energy, about one-third of total global primary energy. Table 2 shows that primary energy use in the buildings sector worldwide grew at an average annual rate of 2.9% between 1971 and 1990. Over the period, growth in buildings energy use varied widely by region, ranging from 1.8% per year in industrialized countries to 7.1% per year in the ROW region. Growth in commercial buildings was higher than growth in residential buildings in all regions of the world, averaging 3.5% per year globally. In 1990, industrialized countries used about 60% of global buildings energy, followed by the EIT (22%), DC-AP (10%), and ROW (9%) countries, respectively.

Between 1990 and 1995, growth in the use of primary energy in buildings slowed in all regions except the industrialized countries where buildings primary energy use climbed at an average of 1.9% per year. The greatest decline occurred in the EIT region due to the economic and political restructuring that began in the late 1980s. As a result, buildings energy use in this region declined an average of 6.8% annually between 1990 and 1995, dominated by a 7.2% per year average drop in residential primary energy use. Growth in buildings energy use in the other two regions – DC-AP and ROW – slowed during this period, but growth rates were still high, averaging 4.8% and 3.8%, respectively.

3.1.3 Primary Energy Demand: Transport

The transport sector consumed slightly over 63 EJ, or about 20% of global primary energy in 1990. Transport sector primary energy use grew at a relatively rapid average annual rate of 2.8% between 1971 and 1990, slowing to 1.7% per year between 1990 and 1995 (see Table 2). Industrialized countries clearly dominate energy consumption in this sector, using 62% of the world's transport energy in 1990, followed by the EIT (16%), the ROW region (12%), and the DC-AP region (10%). The most rapid growth was seen in the DC-AP countries (5.9% per year) and the ROW region (4.6% per year).

Transport energy use dropped dramatically in the EIT region after 1990; by 1995 this region only consumed 11% of global transport energy use. Growth in transport primary energy use also declined slightly in the industrialized countries, dropping from an average of 2.2% per year between 1971 and 1990 to 1.9% per year between 1990 and 1995. High growth continued in the DC-AP and ROW regions, with the DC-AP countries increasing to an average of 7.6% per year between 1990 and 1995.

3.1.4 Primary Energy Demand: Agriculture

The agriculture sector used only 3% of global primary commercial energy in 1990. Unlike the other sectors, the EIT region dominated agricultural energy use in 1990, using 34% of the total, followed by the industrialized countries (30%), DC-AP (26%) and the ROW (10%) regions (see Table 2). Between 1971 and 1990, average annual growth in primary energy used for agriculture was slower in the industrialized countries (2.2% per year) than in the three other regions which ranged between 4.5% and 4.8% per year. Trends in agricultural primary energy use changed significantly in the EIT and ROW regions after 1990, with EIT consumption dropping an average of 10.6% per year and ROW consumption increasing an average of 12.6% per year through 1995.

3.2 Final Energy Demand: Fuels and Electricity

Final energy use grew more slowly than primary energy use in all regions between 1971 and 1995. Fuels dominate final energy use, but the share of fuels dropped from 90% in 1971 to 83% in 1995, reflecting an increased growth in electricity associated with growing urbanization and electrification in many areas of the world. Figure 3 shows that the share of electricity in final energy grew in all regions, although this growth slowed in the EIT region after 1985.

Globally, electricity use grew at an average rate of 4.3% between 1971 and 1990 (see Table 3), significantly higher than the 2.5% and 2.1% per year growth seen in global primary and final energy use, respectively. The highest annual growth rates in electricity use were in the DC-AP and ROW regions, which averaged 8.6% and 7.2% per year, respectively, between 1971 and 1990. Total electricity use was highest in the industrialized countries, which used 60% of global electricity in 1990. Figure 4 shows that commercial buildings had both the largest growth and highest total electricity consumption, followed by residential buildings, industry, and agricultural. Transport consumes very little electricity; electricity's share in final energy in this sector remained virtually unchanged throughout the period. Both commercial and residential buildings showed the buildings showed the largest growth in electricity, averaging about 5.3% per year between 1971 and 1990. Growth in industrial sector electricity averaged 3.5% per year.

Figure 3. Share of Electricity in Final Energy Consumption in Final Energy Consumption by Region, 1971 to 1995.

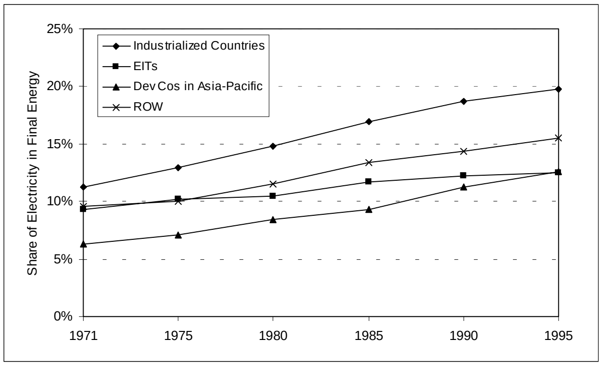
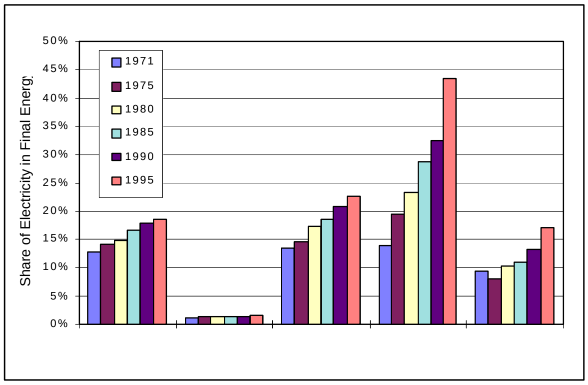


Table 3. Electricity Use by Sector and Region, 1971-1995 (EJ). Reference: IEA, 1997a; IEA, 1997b; BP, 1997.

	1960	1971	1975	1980	1985	1990	1995	AAGR 1960-1990	AAGR 1971-1990	AAGR 1990-1995
Industrial Sector										
Industrialized Countries	2.72	5.43	6.13	7.22	7.54	8.60	9.47	3.9%	2.4%	2.0%
Economies in Transition		2.48	3.17	3.45	4.28	4.44	2.92		3.1%	-8.0%
Dev. Cos. in Asia-Pacific		0.58	0.83	1.24	1.71	2.51	3.43		8.0%	6.4%
Rest of World		0.46	0.66	1.00	1.32	1.51	1.78		6.4%	3.4%
World		8.96	10.78	12.91	14.84	17.06	17.60		3.5%	0.4%
Buildings Sector										
Industrialized Countries	1.94	5.39	6.86	8.57	10.38	12.46	14.21	6.4%	4.5%	2.7%
Residential	*1.19*	*3.25*	*4.04*	*5.05*	*5.86*	*6.81*	*7.63*	*6.0%*	*4.0%*	*2.3%*
Commercial	*0.74*	*2.14*	*2.82*	*3.51*	*4.52*	*5.65*	*6.58*	*7.0%*	*5.3%*	*3.1%*
Economies in Transition		0.62	0.95	1.38	1.68	2.10	1.39		6.6%	-7.9%
Residential		*0.41*	*0.50*	*0.84*	*1.00*	*1.27*	*1.18*		*6.1%*	*-1.4%*
Commercial		*0.21*	*0.45*	*0.54*	*0.68*	*0.82*	*0.20*		*7.5%*	*-24.3%*
Dev. Cos. in Asia-Pacific		0.17	0.24	0.40	0.66	1.12	1.85		10.4%	10.5%
Residential		*0.09*	*0.14*	*0.23*	*0.39*	*0.65*	*1.08*		*10.7%*	*10.7%*
Commercial		*0.08*	*0.11*	*0.18*	*0.28*	*0.47*	*0.77*		*9.9%*	*10.2%*
Rest of World		0.38	0.54	0.89	1.26	1.67	2.31		8.2%	6.7%
Residential		*0.26*	*0.33*	*0.57*	*0.85*	*1.13*	*1.52*		*8.1%*	*6.1%*
Commercial		*0.12*	*0.21*	*0.32*	*0.41*	*0.54*	*0.79*		*8.2%*	*7.9%*
World		6.56	8.59	11.24	13.98	17.35	19.76		5.2%	2.9%
Residential		*4.01*	*5.01*	*6.69*	*8.09*	*9.86*	*11.41*		*4.8%*	*3.0%*
Commercial		*2.54*	*3.58*	*4.55*	*5.89*	*7.49*	*8.34*		*5.7%*	*2.6%*
Transport Sector										
Industrialized Countries	0.11	0.18	0.20	0.22	0.24	0.29	0.33	3.1%	2.5%	2.6%
Economies in Transition		0.24	0.32	0.38	0.44	0.48	0.57		3.7%	3.6%
Dev. Cos. in Asia-Pacific		0.01	0.01	0.02	0.04	0.06	0.10		9.7%	10.2%
Rest of World		0.02	0.02	0.02	0.03	0.03	0.03		2.7%	1.5%
World		0.45	0.55	0.64	0.75	0.85	1.03		3.5%	3.6%
Agriculture Sector										
Industrialized Countries	0.13	0.13	0.10	0.13	0.16	0.18	0.20	1.0%	1.8%	2.3%
Economies in Transition		0.10	0.08	0.13	0.19	0.25	0.22		4.7%	-2.7%
Dev. Cos. in Asia-Pacific		0.09	0.13	0.21	0.25	0.40	0.59		7.9%	8.2%
Rest of World		0.02	0.03	0.06	0.08	0.10	0.17		8.2%	11.6%
World		0.35	0.35	0.53	0.67	0.93	1.18		5.1%	5.1%
All Sectors										
Industrialized Countries	4.91	11.13	13.29	16.14	18.32	21.53	24.21	5.1%	3.5%	2.4%
Economies in Transition		3.44	4.52	5.34	6.59	7.27	5.10		4.0%	-6.8%

Dev. Cos. in Asia-Pacific	0.86	1.22	1.87	2.66	4.08	5.96	8.6%	7.8%
Rest of World	0.88	1.24	1.97	2.68	3.31	4.30	7.2%	5.3%
World	16.31	20.27	25.31	30.24	36.20	39.57	4.3%	1.8%

Figure 4. Share of Electricity by Sector, 1971 to 1995.



3.3 CARBON EMISSIONS

Total global carbon emissions from fuel combustion grew from 3.9 GtC in 1971 to 5.8 GtC in 1990 at an average of 2.1% per year. Growth slowed to 0.6% per year between 1990 and 1995; carbon emissions in 1995 reached 6.0 GtC (Ellis and Tréanton, 1998).[6] Industrialized countries were responsible for almost half of the world's carbon emissions (see Table 4). In these countries, the buildings sector had the largest emissions (915 MtC), followed by the industrial sector (886 MtC), transport (743 MtC), and agriculture (48 MtC). Industrial sector carbon emissions dropped between 1971 and 1990, at an average annual rate of -0.3% per year, while all other emissions grew.

Carbon emissions grew between 1971 and 1990 in the EIT countries, declining after 1990 as energy use dropped significantly (Ellis and Tréanton, 1998). In the former Soviet Union[7], total carbon emissions grew from 561 MtC in 1971 to 948 MtC in 1990, at an average rate of 2.8% per year. Following the start of economic restructuring, carbon emissions dropped to 733 MtC in 1995. In 1990, the industrial sector was responsible for 53% of carbon emissions in the former Soviet Union, followed by the buildings sector (31%), agriculture (9%), and transport (7%). The largest declines in carbon emissions between 1990 and 1995 were experienced in the industrial and transport sectors which both dropped an average of -6.2% per year.

Large increases in energy-related carbon emissions were seen in the DC-AP region between 1971 and 1990. China dominates the DC-AP region, with 1990 emissions of 613 MtC and 1995 emissions of 814 MtC**.** The industrial sector was responsible for 66%, 58%, and 37% of emissions is China, India, and Indonesia, respectively. Energy-related carbon emissions continued to grow at high rates in all three countries between 1990 and 1995.

Between 1971 and 1990, carbon emissions also grew in Brazil, Mexico, and South Africa, all countries in the ROW region. Average annual growth rates in these countries were generally lower than those experienced in China, India, and Indonesia, although the average annual increase in carbon emissions in Mexico of 6% per year was as high as that seen in India over the same period. The industrial sector clearly dominated carbon emissions in Brazil (36%), Mexico (42%), and South Africa (63%) in 1990. Carbon emissions increased in both Brazil and Mexico between 1990 and 1995; only South Africa experienced a decline in carbon emissions during this period, mostly due to decreased emissions in the industrial and buildings sectors.

[6] Our carbon emissions for a country or region differ from IEA values because we only include emissions from fuel combustion, electricity, and heat consumption. IEA CO_2 statistics include a number of other categories, such as unallocated non-energy use, that we did not include.
[7] As discussed in section 2.1, we estimated historical sectoral CO_2 emissions for the former Soviet Union based on IEA data which have many data gaps and uncertainties.

Table 4. Carbon Emissions by Sector for Industrialized Countries and Selected EIT, DC-AP, and ROW Countries (MtC). Reference: IEA, 1997a; IEA, 1997b; IEA, 1997c.

	1960	1971	1975	1980	1985	1990	1995	AAGR 1960-1990	AAGR 1971-1990	AAGR 1990-1995
Industrial Sector										
Industrialized Countries	622.1	931.9	910.8	970.1	858.7	886.6	852.2	1.2%	-0.3%	-0.8%
Economies in Transition										
Former Soviet Union		297.9	361.0	440.4	471.6	506.3	368.1		2.8%	-6.2%
Dev. Cos. in Asia-Pacific										
China		146.9	191.0	256.4	317.6	406.8	568.0		5.5%	6.9%
India		27.7	38.6	44.3	67.2	91.2	118.4		6.5%	5.4%
Indonesia		1.6	2.5	5.7	7.1	11.6	15.3		11.2%	5.7%
Rest of World										
Brazil		8.4	12.3	18.6	16.4	18.7	23.6		4.3%	4.8%
Mexico		10.0	15.0	20.9	27.8	29.4	32.7		5.8%	2.2%
South Africa		26.7	31.2	41.4	40.0	41.6	37.4		2.4%	-2.1%
Buildings Sector										
Industrialized Countries	434.4	790.5	836.2	885.7	886.9	915.5	958.5	2.5%	0.8%	0.9%
Economies in Transition										
Former Soviet Union		174.4	218.1	266.3	276.4	292.3	252.6		2.8%	-2.9%
Dev. Cos. in Asia-Pacific										
China		38.1	51.4	80.6	111.7	136.1	159.5		6.9%	3.2%
India		7.9	8.3	10.6	16.4	26.6	38.8		6.6%	7.8%
Indonesia		2.2	3.7	6.6	8.0	9.4	12.9		8.0%	6.5%
Rest of World										
Brazil		2.6	2.8	3.6	4.0	5.6	6.9		4.1%	4.2%
Mexico		3.0	4.9	7.3	8.7	12.9	15.1		7.9%	3.2%
South Africa		7.5	10.1	10.5	10.9	13.5	11.9		3.2%	-2.5%
Transport Sector										
Industrialized Countries	286.7	494.4	553.8	612.2	635.7	743.0	816.5	3.2%	2.2%	1.9%
Economies in Transition										
Former Soviet Union		51.2	59.5	60.9	67.7	68.4	49.7		1.5%	-6.2%
Dev. Cos. in Asia-Pacific										
China		18.7	18.4	23.5	31.5	39.2	50.5		4.0%	5.2%
India		14.5	15.4	17.1	20.0	23.4	32.7		2.6%	6.9%
Indonesia		2.2	3.2	5.0	5.9	9.2	13.8		7.8%	8.3%
Rest of World										
Brazil		11.7	18.3	20.9	22.0	26.4	32.4		4.3%	4.2%
Mexico		8.6	12.3	19.6	20.6	25.2	27.8		5.8%	2.0%
South Africa		8.7	9.4	8.4	8.6	9.4	11.1		0.4%	3.4%
Agriculture Sector										
Industrialized Countries	21.9	35.2	33.3	37.8	45.1	48.1	51.3	2.7%	1.7%	1.3%
Economies in Transition										
Former Soviet Union		37.4	44.9	60.5	75.3	81.3	62.6		4.2%	-5.1%
Dev. Cos. in Asia-Pacific										

China		12.5	16.8	26.7	25.6	30.6	36.3		4.8%	3.5%
India		1.7	2.9	4.8	7.6	16.2	29.8		12.7%	12.9%
Indonesia		0.2	0.3	0.5	0.9	0.8	1.3		8.2%	9.3%
Rest of World										
Brazil		0.5	1.1	2.0	2.2	2.8	3.7		9.7%	5.4%
Mexico		1.7	2.6	3.9	4.4	2.9	2.7		2.8%	-1.4%
South Africa		0.7	1.0	1.4	1.6	1.8	2.7		5.0%	8.4%
All Sectors										
Industrialized Countries	1365.1	2252.1	2334.2	2505.8	2426.4	2593.2	2678.5	2.2%	0.7%	0.6%
Economies in Transition										
Former Soviet Union		561.0	683.4	828.2	891.0	948.4	732.9		2.8%	-5.0%
Dev. Cos. in Asia-Pacific										
China		216.2	277.6	387.2	486.4	612.8	814.3		5.6%	5.9%
India		51.7	65.2	76.9	111.2	157.5	219.5		6.0%	6.9%
Indonesia		6.1	9.7	17.9	21.8	31.1	43.3		8.9%	6.8%
Rest of World										
Brazil		23.2	34.3	45.1	44.7	53.5	66.6		4.5%	4.5%
Mexico		23.3	34.7	51.7	61.5	70.3	78.3		6.0%	2.2%
South Africa		43.6	51.7	61.7	61.1	66.3	63.1		2.2%	-1.0%

4. Drivers of Energy Use and Greenhouse Gas Emissions

Key drivers of energy use and carbon emissions include activity drivers (total population growth, urbanization, building and vehicle stock, commodity production), economic drivers (total GDP, income and price elasticities), energy intensity trends (energy intensity of energy-using equipment, appliances, vehicles), and carbon intensity trends. These factors are in turn driven by changes in consumer preferences, energy and technology costs, settlement and infrastructure patterns, technical change, and overall economic conditions.

This section focuses on key drivers in the industrial, buildings, and transport sectors.[8] In the industrial sector, energy-intensive industries account for approximately 50% of industrial energy use worldwide and we focus on a specific energy-intensive sub-sector, the iron and steel industry. Buildings trends and drivers are discussed for the entire buildings sector as well as for commercial and residential buildings separately when possible. In the transport sector, examples are given for road, rail, and aviation.

4.1 Activity Drivers of Energy Use and Greenhouse Gas Emissions

Population is the fundamental activity driver and all sectoral-level activity drivers are influenced by trends in population growth. Between 1970 and 1990, world population increased 30%, with the bulk of growth in the DC-AP and ROW regions (UN, 1996). Globally, this increase averaged 1.8% per year, led by 2.6% average annual growth in the ROW region and 2.0% average annual growth in the DC-AP region. Industrialized countries and the EIT both had moderate population growth, averaging 0.8% per year. World population growth slowed between 1990 and 1995, averaging only 1.5% per year.

Sectoral-level activity, while driven by trends in population growth, is measured differently in each of the end use sectors; in industry activity is based on commodities produced, in buildings it is based on number of households or square meters of living or commercial space, and in transport is it based on vehicle stocks. Regardless of how activity is measured, though, there are factors specific to each sub-sector that drive activity levels, which in turn are related to energy use and greenhouse gas emissions.

4.1.1 Industrial Sector Activity Drivers

Generally, industrial production has been growing in most economies. Industrial production can be measured using either economic or physical indices. At an aggregate level, monetary values such as value added, value of shipments, and production value are the most commonly used terms for describing production, although various physical production indices are available to measure production of specific commodities. Manufacturing value added per capita has been growing in most regions, except there has been a decline recently in the EIT region and in most African countries over the past 15 years. The share of manufacturing value added of GDP is around 30% for most regions in the world, as shown in Figure 5. The only exception is the EIT region which has a very large share of industrial production in the economy.[9] The economic transition process occurring in these countries has led to a severe reduction of industrial production in recent years.

Figure 5 also shows that the share of manufacturing value added is increasing in countries such as those in the DC-AP region, while showing a small decline in the economies of industrialized countries due to continuous restructuring away from industrial activities and toward more service activities. For example, the industrial sector share dropped from 42% in 1970 to 35% in 1990 in the Western Europe region, while increasing from 24% to 33% and from 27% to 40% in China and Eastern Asia, respectively. In the former Soviet Union, the manufacturing share dropped from 60% to 55% during this period (RIVM, 1998).

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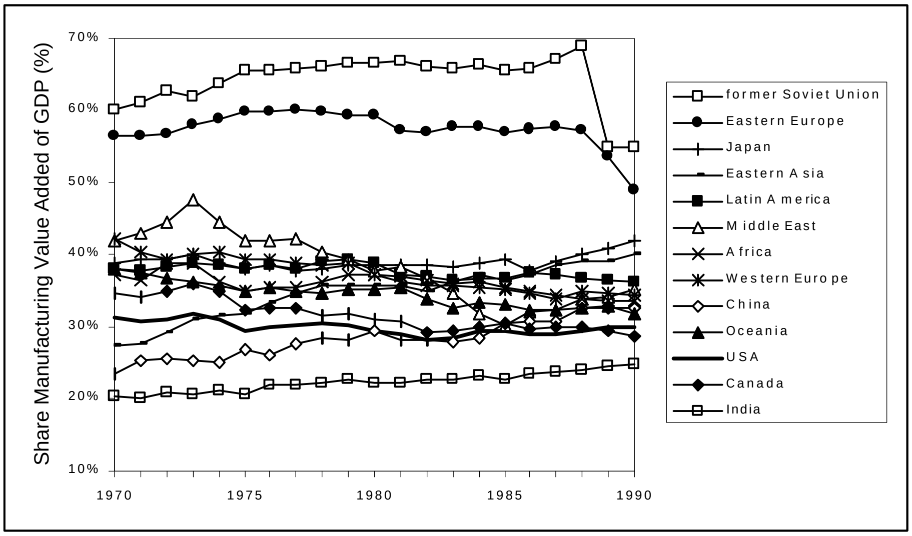
[8] The agriculture sector is not included in this discussion; readers are directed to Cole et al., 1996 and Worrell et al., 1997a for further information on trends in this sector.

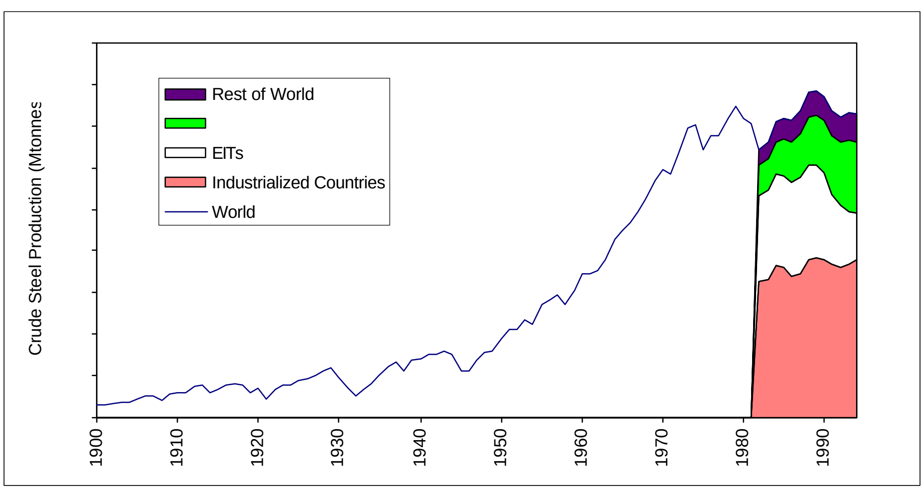
[9] Note that the concept of GDP may not be fully compatible with other means to express the production volume used in the former centrally planned economies.

Figure 5. Historical Trends in Manufacturing Value Added, Expressed as Share of GDP (in 1990 US$) for 13 Regions, 1970-1990. Reference: RIVM, 1998.



The industrial sector is dominated by the production of a few major energy-intensive commodities such as steel, paper, cement, and chemicals. In any given country or region, production of these basic commodities follows the general development of the overall economy. Rapidly industrializing countries will have higher demands for infrastructure materials and more mature markets will have declining or stable consumption levels. Global steel production increased from 28 Mtonnes in 1900 to 730 Mtonnes in 1994 (IISI, 1996), at an average growth of 3.4% per year (see Figure 6). In the industrialized countries, steel production is growing slowly, at a rate of just over 1% per year, and is expected to level off in the near future (Wödlinger et al., 1997). Steel production in the EIT region declined in recent years due to the economic restructuring process.

Figure 6. Global Steel Production from 1900 to 1994 With Regional Distribution of Production for 1982 to 1994. References: IISI, 1996; Wödlinger et al., 1997.



In contrast, production of steel in developing countries has been 6.6% per year on average (IISI, 1996), and is expected to be the main driver for continued growth in global steel production. Recently, the Asian region experienced high average annual growth in steel production of about 7.5% per year. In the medium term Asia is expected to be main growing consumer of steel. The low per capita consumption of steel in developing countries (51 kg/capita in 1991) compared to the high levels in industrialized countries of over 300 kg/capita (IISI, 1996), shows that there is still a large potential for growth in production in these countries.

The regional differences in consumption patterns (expressed as consumption per capita) will fuel a further growth of consumption in developing countries. Many commodities, including steel, are traded globally and regional differences in supply and demand may remain in the future. Trends also depend on regionally availability of resources (e.g. scrap) and capital. Therefore, a link between consumption and production by region is not easy to estimate or to model. Table 5 presents an overview of regional growth of steel production showing that production in industrialized countries and the EIT region, while strong in the 1950 to 1990 period, dropped considerably between 1990 and 1995. As expected, growth in production was large in both the DC-AP and ROW regions for the entire period (Wödlinger et al., 1997).

Table 5. Historical Growth of Steel Production in Various Regions and the World. References: IISI, 1996; Van Vuren, 1995; Wödlinger et al., 1997.

Region	Growth 1950-1990 (% per year)	Growth 1985-1995 (% per year)
Industrialized Countries		
Western Europe	3.0%	0.5%
North America	0.3%	1.1%
Japan	8.1%	-0.7%
Oceania	4.5%	3.0%
EITs		
Eastern Europe & former Soviet Union	4.4%	-6.4%
DC-AP		
China	16.6%	7.1%
Other Asia	9.5%	7.0%
Rest of World		
Latin America	8.7%	2.4%
Middle East	11.1%	11.0%
Africa	6.6%	1.0%
World	3.6%	0.2%

4.1.2 Buildings Sector Activity Drivers

Along with population size, key activity drivers of energy demand in buildings are rate of urbanization, number of households, per capita living area, persons per residence, and commercial floor space. As populations become more urbanized and areas become electrified, the demand for energy services such as refrigeration, lighting, heating, and cooling increases. In the residential buildings sector, the level of energy demand is further influenced by population age distribution, household income, number of households, size of households, and the number of people per household. In the commercial buildings sector, demographic factors that influence energy demand include the overall population level (i.e., the number of people desiring commercial services) and the size of the labor force.

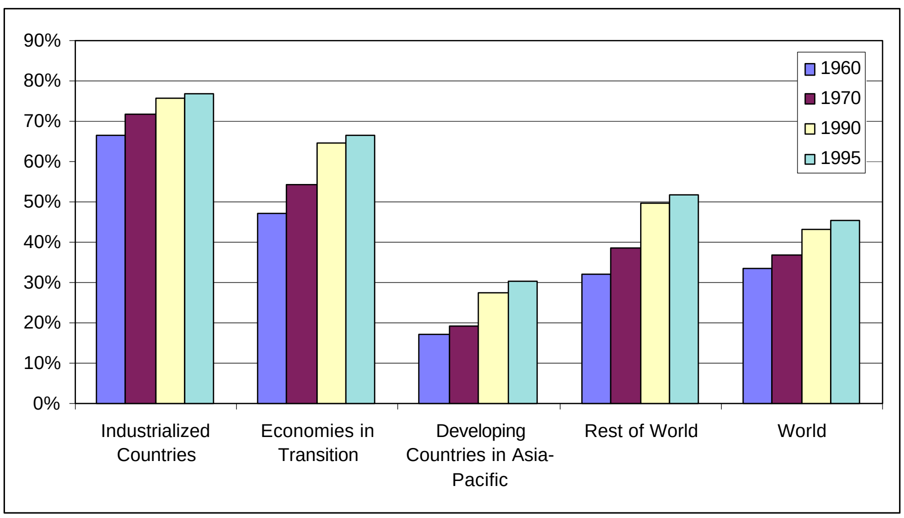
The number of people living in urban areas increased between 1970 and 1990, growing from 1.35 billion, or 37% of total, in 1970 to 2.27 billion, or 43% of total, in 1990. Growth in urbanization was strongest in the DC-AP and ROW regions, where the average annual increase in urban population was nearly 4.0% per year (see Figure 7). Much slower growth was seen in the already relatively urbanized industrialized and EIT regions. Increasing urbanization in the DC-AP and ROW regions leads to the increased use of commercial fuels, such as kerosene and liquified petroleum gas, for cooking instead of traditional biomass fuels. Additional increases in energy use come with electrification, when appliances and lighting are adopted. In general, higher levels of urbanization are associated with higher incomes and increased household energy use (Sathaye et al., 1989; Nadel et al., 1997).

Globally, the number of people living together in a household (defined as a separate living unit) tends to decline with increasing income and urbanization of the population. In industrialized countries, household size dropped from an average of 3.5 persons per household in 1970 to 2.8 persons per household in 1990. This decline in household size lead to an increase in the total number of households in the region, where households grew 1.5% per year faster than population between 1970 and 1991 (Schipper and Meyers, 1992). Energy use per household declined as household size dropped; however, residential energy use per capita increased during this period (IEA, 1997d).

In the EIT region, the number of persons per household has also declined recently, dropping from 3.7 to 3.5 between 1978 and 1988 in Poland and 3.0 to 2.8 between 1980 and 1991 in the Czech Republic (Meyers et al., 1995). In 1989, Russia and Ukraine each had an average of 3.2 persons per household (World Bank, 1995). Much larger household sizes are common in the DC-AP and ROW regions. For example, average household size in China dropped from 5.2 persons per household in 1981 to 4.0 persons per household in 1995 (World Bank, 1995; Turiel et al. 1998). Between 1970 and 1995, average household size dropped from 5.9 to 5.4 in the Philippines, from 5.5 to 4.0 in S. Korea, from 6.5 to 4.8 in Thailand, and from 5.4 to 4.2 in Brazil (LBNL 1998b; Turiel et al., 1998).

Either commercial sector GDP or commercial sector floor space can be used to measure activity in commercial buildings. The commercial sector share of GDP is high in industrialized countries and has been growing rapidly in recent years. A survey of ten industrialized countries showed that commercial sector GDP grew an average of 3.3% per year from 1970 to 1995, with even higher rates experienced in some countries like Japan and Finland (Schipper and Meyers, 1992). In 1995, the overall GDP commercial sector share was 66% in thirteen industrialized countries (Krackeler et al. 1998). Although some industrialized countries collected detailed data on commercial floor area, this is a more difficult measure of activity due to lack of data for many regions of the world.

Figure 7. Percentage of Population Living in Urban Areas by Region, 1960, 1970, 1990, 1995. Reference: U.N. 1996.



4.1.3 Transport Sector Activity Drivers

Statistics on road vehicle production and fleets are quite reliable in industrialized countries but may be less so elsewhere. Manufacturers maintain comprehensive records of vehicle production, while governments maintain records of registered vehicles. However, vehicle registration is usually a basis for charges or taxes, providing an incentive for evasion where policing is weak. Statistics may be difficult to interpret, because definitions of vehicle types differ among countries. This variation applies in particular to the categorization of “light trucks” and “vans” which are rapidly replacing cars as personal vehicles in many high-income countries, but are defined in statistics for the United States, for example, as “commercial vehicles”.

Road vehicle fleets have grown significantly in recent decades, jumping from 70 million motor vehicles in 1950 to over 670 million in 1996 (see Table 6). The global rate of growth has followed an S-curve and has declined in recent decades, from nearly 5% per year during the 1950s to about 2.5% per year during the 1980s.

Until 1970, the Group of Seven (G7) countries (France, Germany, Italy, United Kingdom, Canada, U.S., and Japan) accounted for 80% of the world's motor vehicle fleet. While other countries have seen more rapid growth in the last two decades, the world fleet remains heavily concentrated in industrialized countries. Countries in the DC-AP and ROW regions account for 10% of cars and 23% of commercial vehicles.

Table 7 summarizes the regional split of traffic and transport energy use for 1992 (WEC, 1995b). Countries vary widely in the completeness and quality of their road and rail traffic statistics. Road traffic is usually estimated on a national basis from roadside vehicle counts. In some countries such data are corroborated using vehicle odometer readings. However, other countries have infrequent traffic surveys, and may estimate traffic volumes based on vehicle populations or on fuel demand statistics. Freight movements (tonne-km) are usually estimated from haulers accounts. Rail passenger and freight traffic may be less uncertain, as the number of companies involved is relatively small and most rail operators maintain traffic statistics. Nevertheless, ticket sales give only an indication of the level of travel, with accurate statistics depending on surveys of actual numbers of passengers in trains. Air traffic is most reliably known, as airlines have to account accurately for both passengers and freight on each sector flown. Total fuel consumption by each transport mode (road, rail, air) is accurately known in most countries. However, the breakdown of fuel use within modes is not so well known except where governments or companies have undertaken detailed surveys to establish the fuel consumption by different types of traffic. World Energy Council (WEC) estimates of car fuel economy are broadly consistent with those from other sources identified in the IPCC Second Assessment Report (Michaelis et al., 1996).

Table 6. Motor Vehicle Fleet Growth 1950 to 1996, Selected Countries, Millions. Reference: AAMA, 1996.

	1950	1960	1970	1980	1990	1996
Industrialized Countries						
France		6.49	13.71	20.99	27.76	30.76
Germany		5.59	15.47	24.57	32.15	43.56
Italy	0.58	2.43	11.11	19.12	29.91	33.52
United Kingdom	3.37	7.18	13.57	17.36	26.30	28.49
Canada		5.16	8.08	13.21	16.55	16.82
United States	49.16	73.86	108.42	155.80	188.80	206.37
Japan		1.29	17.25	37.07	56.49	67.20
Spain			4.12	8.96	14.44	17.95
Australia			4.78	7.26	9.78	10.75
EIT Countries						
Czech Republic & Slovakia	0.20	0.37	1.04	2.63	3.74	4.92
Developing Countries in Asia						
China				1.68	5.84	11.45
India		0.54	1.12	1.88	4.23	6.75
Rest of World						
Argentina		0.87	2.27	4.33	5.88	6.07
South Africa	0.62	1.21	2.07	3.40	5.09	6.28
Rest of the World				92.73	156.02	180.48
World	**70.40**	**126.89**	**246.38**	**410.98**	**582.98**	**671.36**

Various factors in addition to transport costs and income affect travel activity, including household size, the occupation of the head of the household, household makeup, and location (Hensher et al., 1990; Jansson, 1989; Walls et al., 1993). People in higher-skilled occupations, requiring higher levels of education, are more price- and income-responsive in their transport energy demand than people in lower-skilled occupations (Greening and

Jeng, 1994; Greening et al., 1994). Families are more price- and income-responsive in the early years of child-rearing than in the later stages.

Table 7. Estimated 1992 Transport Activity Levels. Reference: WEC, 1995b.

	World	Regions			
		Industrialized Countries	EIT Countries	Developing Countries in Asia-Pacific	Rest of World
Cars					
Fleet (million)	**470**	374	36	25	35
Energy use (l/100 km)	**11.5**	11.3	11.4	13.0	12.9
Total travel (10^{12} km)	**6.81**	5.59	0.4	0.37	0.45
Total energy (PJ)	**27.07**	21.83	1.57	1.66	2.01
Freight					
Total Freight (t-km)	**12911**	4956	4735	2240	980
Rail Share	**59%**	43%	83%	62%	19%
Energy Intensity (kJ/tkm) trucks	**4784**	3616	5367	5956	7059
Energy Intensity (kJ/tkm) rail	**376**	302	373	475	548
Road Freight Energy Use (EJ)	**25.08**	10.13	4.25	5.07	5.63
Rail Freight Energy Use (EJ)	**2.88**	0.65	1.47	0.66	0.1
Aviation					
Passenger-km (billion)	**1947**	1365	160	293	129
Freight (billion tonne-km)	**243**	170	16	42	15
Passenger Energy Intensity (kJ/pkm)	**2500**	2330	3500	2491	2946
Freight Energy Intensity (kJ/tkm)	**19800**	18235	28125	20000	28000
Passenger Energy Use (PJ)	**4.85**	3.18	0.56	0.73	0.38
Freight Energy Use (PJ)	**4.81**	3.1	0.45	0.84	0.42

Use of transport services evolve as incomes rise, costs fall, and priorities change. A number of stages in the use of transport systems can be identified, corresponding roughly to Maslow's hierarchy of needs (Maslow, 1954):

1. essential survival needs: movement of food, fuel, water, and travel for health care and to escape danger
2. needs relating to economic security: movement of traded goods — mostly primary commodities — and travel to work and for education
3. needs relating to social involvement: visiting family and friends, travel to entertainment, and family vacations. Goods transport moves beyond essentials to include more manufactured goods.
4. needs relating to self-expression and exploration: tourism, and more distant vacations. Goods transport moves towards very-high-value-added goods.

This pattern is reflected in transport statistics and travel surveys, which indicate that, as societies become wealthier, social and leisure travel become more important. The car has been an essential element in this process, allowing increasing flexibility, especially in social relationships. The development of air travel has allowed tourism to flourish.

Urban layout both affects, and is affected by, the predominant transport systems. It is also strongly influenced by other factors such as people's preference for living in low-density areas, close to parks or other green spaces, away from industry and close to schools and other services. Travel patterns may be influenced by many factors including the size of the settlements, proximity to other settlements, location of workplaces provision of local facilities and car ownership.

While there does appear to be an inverse correlation between urban density and transport energy use experts disagree on the size of the effect. The link between settlement patterns and energy use for transport can be explored in several ways which give different results (Banister 1992). For example, in the United Kingdom, Londoners use more energy than people in smaller cities but people living in rural areas use about 50% more energy than Londoners, partly because they travel further and partly because they are more reliant on cars. In the

United States, people living in rural areas use about a third more energy than people living in city centers. These differences seem to relate partly to settlement pattern, but other factors are likely to be important too, not least differences in the income, car access, household size and age of the populations.

Detailed analysis of travel patterns in specific settlements reveals more complexity, with transport energy use influenced by the size of the settlements, proximity to other settlements, location of workplaces provision of local facilities and car ownership

A survey of cities around the world (Newman and Kenworthy, 1990) found that population density was strongly and inversely correlated with transport energy use. Energy use rises dramatically when density falls below 29 people/ha but is independent of settlement size. Armstrong (1993) uses the Newman and Kenworthy data for a time series analysis, confirming that a correlation exists, but finding that it is smaller than that found by Newman and Kenworthy. International comparisons are very difficult as, where surveys exist they have frequently used different definitions. Meanwhile, the existence of a correlation does not prove causality: differences and changes in travel patterns may have influenced urban density.

4.2 Economic Drivers of Energy Use and Greenhouse Gas Emissions

Many macroeconomic projections of energy use and greenhouse gas emissions rely on historical data to estimate price and income elasticities for energy demand and then use projections of GDP and energy prices to generate energy and emissions projections. The relationship between total final sector energy use and economic drivers such as GDP per capita varies across countries depending upon the sector. We found a relatively strong relationship in the transport and buildings sectors and a moderate relationship in the industrial sector. Other economic indicators, such as level of economic development in the industrial sector and personal consumption expenditures in residential buildings, are more closely correlated with energy use in these sectors.

Income elasticities vary widely among different types of energy services and the country or region under consideration. For example, the income elasticity of refrigerator ownership in most industrialized countries is extremely low, as most households already own a refrigerator. The elasticity is much higher in medium-income countries with low refrigerator ownership. In general, income elasticities for ownership or use of appliances are lowest for very low income countries, highest for medium income countries where a substantial portion but not the majority of the population can afford the appliance, and intermediate for high income countries where the vast majority of the population already have access to the appliances.

4.2.1 Industrial Sector Economic Drivers

In the industrial sector, empirical studies have shown that economic development rather than price elasticity may be the major factor explaining trends in material intensity because elasticity of industrial demand for resources (including energy) varies widely due to the diverse activities, production cost breakdowns, and technologies used in industrial production (Evans, 1996). Figure 5 shows that the correlation between industrial final energy use and GDP[10] is moderate (R^2 = 0.6). This measure, which includes the energy intensity of industrial production, the structure of the industrial sector, and the demand for industrial production illustrates that modeling trends in industrial energy consumption is not straightforward.

Greenhouse gas emissions and energy use by industry are still dominated by a relatively small number of basic energy-intensive industries (WEC, 1995a). These industries are primarily involved in upgrading natural resources to materials used in society and are relatively large emitters of pollutants and greenhouse gases (Jänicke et al., 1997). Material consumption is still increasing and this growth is apparent for “classic” materials (e.g. cement, steel) and for the “new” materials (e.g. plastics, aluminium). Studies of material consumption in industrialized countries have shown that consumption (expressed as apparent consumption per capita or unit GDP[11]) increases in the initial development of society to a maximum, and eventually saturates or even declines.

[10] GDP values are presented in terms of purchasing power parity (PPP) rather than market exchange rates because it has been shown that there is a stronger correlation between energy use and GDP when this value is calculated using PPP rather than market exchange rates (Siddiqi, 1994).

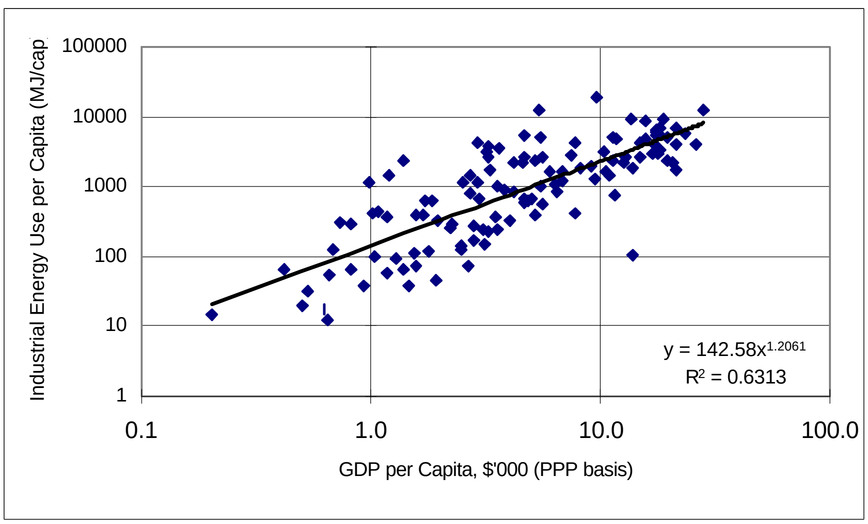
[11] International statistical data give the apparent consumption of materials, i.e. the intermediate consumption of materials in industry. Due to increasing import and export streams of products (containing the materials) the figures represent the consumption by the economic production sectors, rather than the end-use of the society. The first detailed analyses of end-use in some countries are available but not yet as time series. The availability

Trends in materials use in industrialized countries show saturation on a per capita basis. Expressed as function of unit GDP, material intensity declines after reaching a maximum (Williams et al., 1987).

In Figure 9 the historical trends in apparent consumption of steel are depicted for the U.S. and Germany expressed as consumption of steel per capita and per unit GDP. The initial increase is caused by large investments required in building an industrial infrastructure. In later stages, material substitution and competition between materials as well as a shift to a more service-oriented economy contribute to a decrease in the material intensity of societies (Malenbaum, 1975; Williams et al., 1987; Bernardini and Galli,1993). For example, the substitution of classical steels by aluminium in transport applications led to the development of high strength steels that can compete with aluminium. Because of improved properties, less material is needed to fulfill the service, leading to declining material intensities. The inverse U-shaped curve as developed by Malenbaum (1975) cannot always explain irregular developments in material intensity trends (Evans, 1996). Recycling appears to increase with development (Bernardini and Galli, 1993), as can be seen from the increasing post-consumer recycling rates in the industrialized world. The development curves seem not only to be valid for construction materials but also for other commodities like food (Bernardini and Galli, 1993), fertilizers (Williams et al., 1987), and pesticides. In addition, Bernardini and Galli (1993) suggested that the maximum intensity declines if reached later in time by a given economy or society. However, most analyses have been performed only for industrialized countries. The need for further analysis is stressed by the current situation in rapidly-industrializing countries like South Korea that have a very high per capita apparent consumption of steel which is used in large exporting industries like car manufacture and ship building.[12] The industry in South Korea is heavily dependent on exports of these material-intensive products, determining the material intensity of the economic activities, rather than the intensity of society.

Although the use of all materials in developing countries will certainly grow, per capita consumption may not be as high as in the industrialized countries. The level of saturation depends on many factors, including technology transfer but also infra-structural (including economic structure) policy choices (Jänicke et al, 1997).

Figure 8. Relationship Between 1995 Industrial Final Energy Use per Capita and GDP in 122 Countries. Reference: IEA 1997a; IEA 1997b.



and comparability of GDP data is often difficult, as we know from energy intensity analyses, see e.g. (Schipper and Meyers, 1992; Martin et al., 1995). Comparisons of the material intensity, expressed as material use per unit GDP, should be interpreted carefully.

[12] This case shows that the available statistics are not yet suited to prove that countries developing later in time will reach a lower saturation level, as stated by Bernardini and Galli (1993).

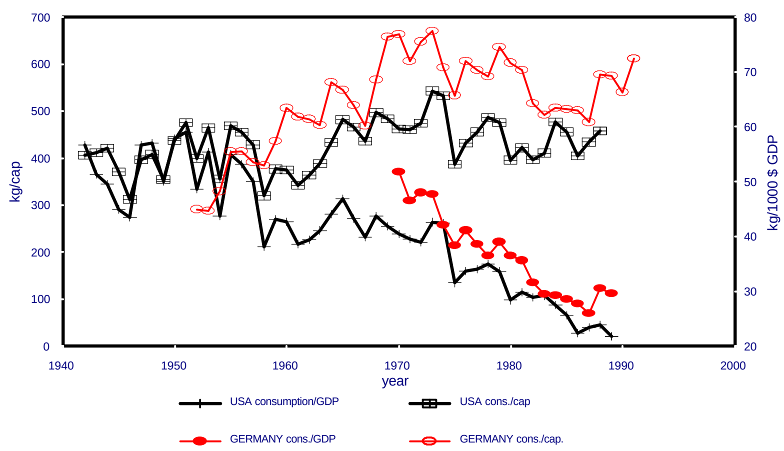
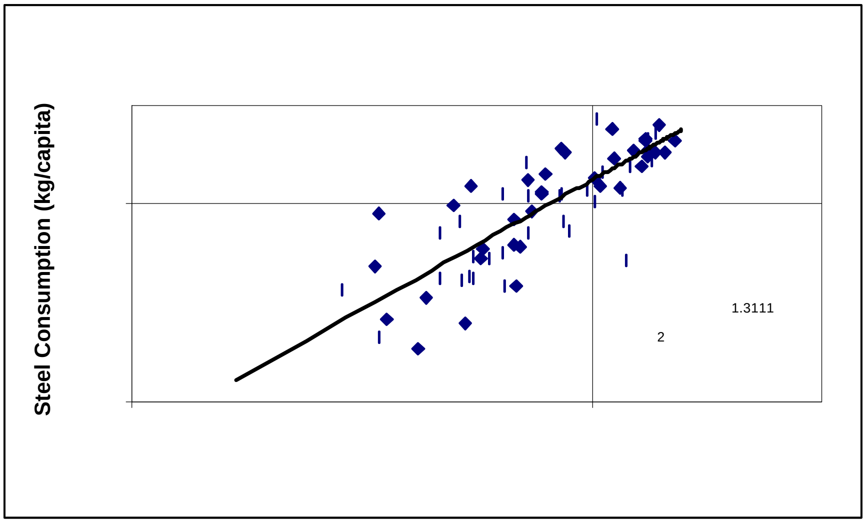


Figure 9. Apparent Steel Consumption in the U.S. and Germany for the Period 1940-1990 (depicted as function of GDP and per capita). Reference: Worrell et al., 1997a.

Various economic indicators are commonly used at the level of individual industrial sub-sectors, e.g. value added, production value, value of shipments, while physical indicators are under the development for a wide range of industrial sub-sectors (Phylipsen et al., 1997). Physical indicators are more closely linked to technical efficiency, but can only be used for relatively homogeneous activities (Schipper and Meyers, 1992). Where energy services are explicitly modeled, they are usually assumed to be dependent on GDP or per-capita income, and price or cost. The link might be made through constant income and price elasticities of absolute demand for a service, through a logistic curve, or through income elasticities that fall with increasing income. In general equilibrium models, energy services demand may be estimated using a system of nested production functions ultimately delivering final consumption.

An historical analysis of the European steel market showed that steel demand has also been reduced in periods of low economic growth, and showed that diffusion of new technology is mostly responsible for reduced material intensity, rather than income growth (Mannearts, 1997). Steel production and industrial production can be modeled using growth in population, income, and developments in materials intensity (or intensity of use). Figure 10 depicts the relatively weak link between income per capita and apparent steel consumption.

Figure 10. National Per Capita Apparent Consumption of Crude Steel as a Function of GDP per Capita in 1994. References: IEA 1997a; IEA, 1997b; IISI, 1996.



4.2.2 Buildings Sector Economic Drivers

In the buildings sector, we found a relatively strong relationship across countries between GDP per capita and final energy use in residential (R^2=0.77) and commercial buildings (R^2 = 0.78) using data for 25 industrialized countries, China, and the regions of Asia, Africa, Latin America, and Middle East (see Figures 11 and 12). Energy use in buildings is not only influenced by economic variables, but also by climate, energy-related policies, house size or commercial building floor area, and consumer energy-using behavior patterns.

Energy consumption in residential buildings is strongly correlated with household income levels. Between 1973 and 1993, increases in total private consumption translated into larger homes, more appliances, and an increased use of energy services (water heating, space heating) in most industrialized countries (IEA, 1997d). In general, countries with colder climates have higher incomes as well as higher heating levels. Household size, a key determinant of residential energy use, has grown with personal consumption expenditures in most industrialized countries, led by the United States where economic policies granting tax reductions on home loan interest have contributed to that country having the largest average home sizes in the world.

In developing countries, urban areas are generally associated with higher average incomes (Sathaye and Ketoff, 1991). Wealthier populaces in developing countries exhibit consumption patterns similar to those in industrialized countries, where purchases of appliances and other energy-using equipment increase with gains in disposable income (WEC, 1995a). Modern fuels such as kerosene, LPG, and electricity account for more than 90% of household energy consumption in high income homes in India, while lower income homes consume less than 50% of these commercial fuels (IEA, 1995). An important finding, though, is that purchased household energy use rises less rapidly than income, suggesting that there is a level of saturation of energy-using equipment. In industrialized countries, household energy consumption has slowed as equipment penetration rates reach saturation (IEA, 1997d).

In the commercial sector, the ratio of primary energy use to total GDP as well as commercial sector GDP fell in a number of industrialized countries between 1970 and the early 1990s. This decrease occurred despite large growth in energy-using equipment in commercial buildings, almost certainly the result of improved equipment efficiencies. Electricity use in the commercial sector shows a relatively strong correlation with commercial sector GDP, although there is a wide gap in electricity use at any given level of commercial sector GDP (IEA, 1997d).

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Figure 11. Relationship Between 1995 Residential Buildings 1995 Commercial Buildings
Final Energy Use per Capita and GDP per Capita in 25 Industrialized Countries, China, and the Regions of Asia, China, and the Regions of Asia, Africa, Latin America, and Middle East. References: IEA, Middle East. References: IEA, 1997a; IEA, 1997b.

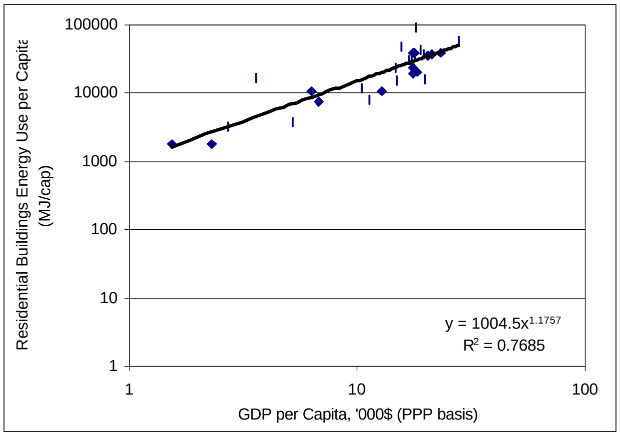
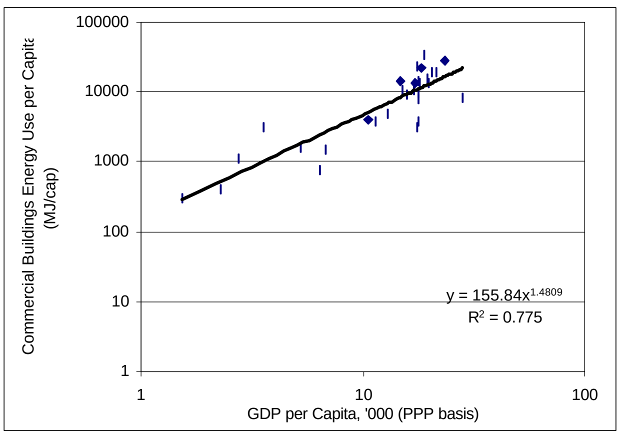


Figure 12. Relationship Between Final Energy Use per Capita Industrialized Countries, Africa, Latin America, and 1997a; IEA, 1997b.

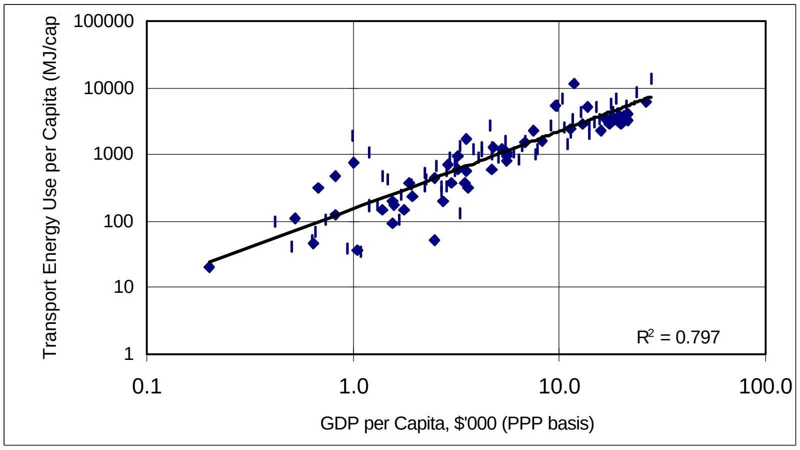


4.2.3 Transport Sector Economic Drivers

International comparisons reveal a strong correlation between transport final energy use and GDP. The data plotted in Figure 13 indicate a GDP elasticity of 1.2, with R^2 = 0.8. Nevertheless, at a given level of GDP, energy use can vary by a factor of two or more, and the growth of transport energy use with income and time varies considerably among regions (see Figure 13). Analysts have found a close correlation between road-freight traffic (tonne-km) and GDP (Bennathan et al., 1992), whereas rail freight appears to be almost independent of GDP, but is very closely related to country surface area.

Studies in the past have found that the income elasticity of transport energy demand is relatively low for the lowest-income countries, high for medium-income countries, and again low for the highest-income countries. However, as can be inferred from the regional trends in Figure 9, the pattern of growth is not that straightforward. Important factors in addition to income level include changes in economic structure, the quality and density of infrastructure, and fuel prices.

Figure 13. Relationship Between 1995 Transport Energy Use per Capita and GDP per Capita in 122 Countries. Reference: IEA 1997a; IEA 1997b.



Many of the existing models of car choice (e.g. Mogridge, 1983; Greene and Duleep, 1993; Bunch et al., 1993; Koopman, 1995; U.S. DOE, 1995; Segal, 1995) implicitly assume that consumers behave, at least on average, in a rational way to maximize a utility function. Most applications of these models (e.g. Greene and Duleep, 1993; U.S. DOE, 1995) implicitly assume that this utility function is time- and location-invariant. However, many alternative models of choice are possible and analysts have questioned these assumptions (Dietz and Stern, 1993; Jacobs, 1994).

A wide variety of factors are taken into account by those purchasing vehicles, including purchase and running costs, reliability, and match with the purchaser's needs. Different purchasers will emphasize different attributes. Studies evaluating the trade-offs made by consumers between fuel economy and other vehicle attributes find (or make assumptions that imply) that consumers will be prepared to pay $82 to $370 per liter per 100 kilometer fuel economy improvement (Michaelis and Davidson, 1996). Many econometric studies have been made of the effects of car and fuel prices on the numbers of cars purchased, the energy efficiency of those cars and the distance they are driven (see Table 8).

There is less information available on price elasticities of freight energy demand, although several studies have estimated price elasticities of freight transport of various commodities and are reviewed by Oum et al. (1990), who find that a 10% increase in freight transport costs leads to a reduction in demand in the region of 7 to 11%, aggregated over different commodities. This is highly variable by commodity, with higher responses for transport of raw materials and lower responses for final products. The effect of price is likely to be high on the use of large trucks, for which energy use constitutes up to 25% of total costs, and low on the use of small trucks, for which energy use can constitute less than 10% of costs. Thus, short term fuel price elasticities might be expected to be in the range of -0.1 to -0.2.

Vouyoukas (1993) finds that freight traffic (tonne-km) decreases by about 2% for a 10% increase in fuel price. International comparisons (based on Bennathan et al., 1992) indicate that the effect of fuel price on freight traffic is very hard to separate from other influences, but an elasticity in this region of -0.1 is possible. Greene (1992) finds that short run fuel price elasticities of freight demand in the United States are very hard to detect and probably less than 0.1.

Table 8. Long-Run Price Elasticities of Car Demand and Use. References: Dahl and Sterner, 1991; DRI/McGraw-Hill, 1997; Fowkes et al., 1993; Goodwin, 1992; Greene, 1992; Greening et al., 1994; Hausberger, 1996; Jones, 1993; Mogridge, 1983; Walls et al., 1993.

Dependent Variable	Independent Variable	Price Elasticity Range	
		Long run	Short run
Traffic (aggregate car use in vehicle-km)	Gasoline price	-0.3 to -0.5	-0.1 to -0.3
Car ownership	Gasoline price	-0.1 to -0.3	
Car use (km per year per car)	Gasoline price	-0.1 to -0.3	-0.1 to -0.3
Gasoline consumption	Gasoline price	-0.5 to -1.6	-0.1 to -0.6
Fuel economy (L/100 km) pure efficiency	Gasoline price	-0.1 to -0.2	
Fuel economy (L/100 km) downsizing	Gasoline price	approx. -0.06	
Fuel economy (L/100 km) behavior	Gasoline price	-0.1 to -0.2	-0.1 to -0.2
Car ownership	Car price	-0.4 to -1.6	

The long run response of diesel fuel demand to price changes is expected to be somewhat stronger than the response of total traffic, as there is likely to be a technology response. International comparisons based on Organization for Economic Cooperation and Development (OECD) and IEA country data for the mid-1980s indicate a figure in the region of -0.4, and this is consistent with the long-run elasticities calculated using the IEA world energy model (IEA, 1994b). Time series data for 22 OECD countries in the late 1980s indicate short-run diesel fuel demand elasticities with respect to GDP in the region of 1 to 2, and with respect to fuel price in the region of -0.3 to -0.35 (Michaelis, 1996). These figures are averages, and the variation over time and between countries is considerable. It should be noted that price of and demand for commodities, including oil, coal, steel and cement, is likely to be affected by the same world market changes that influence the price of diesel fuel, so that any price effects may not just be due to changes in the cost of freight transport.

Econometric studies (e.g. ICAO, 1995a) find that the GDP elasticity of air traffic (tonne-kilometers performed or TKP) is in the region of +2. In fact, air traffic grew about three times as fast as GDP in the early 1970s, but only about twice as fast since the early 1980s. After allowing for the effects of continually falling prices, the elasticity of the 10-year average growth rate with respect to the 10-year average GDP growth is not much more than 1.0 (Michaelis, 1997). Meanwhile, it is possible that oil price increases in 1973 to 74 and 1979 to 80 had some effect on the rate of price reduction, but any effect on the rate of traffic growth appears to have been slight.

4.3 Energy Intensity Trends

Energy intensity is the amount of energy used to perform a particular service such as producing a tonne of steel, powering a refrigerator, or propelling a vehicle. Technical progress generally leads to improved energy efficiency in technologies such as lights, vehicles, refrigerators, and manufacturing processes. In theory there are large potentials for energy savings. Using the thermodynamic concept of exergy, Ayres (1989) estimates that the U.S. uses its primary energy sources with only a 2.5% efficiency when fulfilling its energy services illustrating that there is a substantial theoretical potential for energy intensity improvement. Jochem (1989) has stated that a 50% reduction in energy demand in industrialized countries is technologically feasible, and in the long term even an 80% reduction of the current primary energy consumption is possible. For industrial processes thermodynamic principles are used to calculate the theoretical efficiency and hence the maximum potential for energy savings. Several authors have assessed the minimum energy requirements of an activity, e.g. (Szargut and Morris,1987; Wall, 1988). Other studies have shown that considerable energy efficiency improvement can be realized (technically and economically) in the short term (10 to 15 years) with available technologies (Nakicenovic, 1993; Lovins and Lovins, 1991; WEC, 1995a; Worrell et al., 1997b).

4.3.1 Industrial Sector Energy Intensity Trends

Energy intensity in the industrial sector can be measured using both economic and physical indices. Economic energy intensity measurements (e.g. energy use/economic output) are useful for characterizing the entire industrial sector or for those portions of the industrial sector that are not easily measured in physical terms. Physical energy intensity measurements (e.g. energy use/tonne of product), also called specific energy consumption, more accurately reflect trends in energy efficiency, but are typically limited to use in the energy-intensive industrial sub-sectors. Evaluations of these two means of measuring energy intensity have shown that economic energy intensity values do not always accurately reflect physical energy intensity trends, making physical energy intensity measurements the preferred metric where possible (Worrell et al., 1997b; Freeman et al., 1996).

In aggregate terms, studies have shown that technical efficiency improvement of 1 to 2% per year is possible in the industrial sector and has occurred in the past (Ross and Steinmeyer, 1990). Energy requirements can be cut by new process development. In addition, the amount of raw materials demand by a society tends to decline as countries reach certain stages of industrial development which leads to a decrease in industrial energy use. The accounting of trends in structural shift, material intensity and technical energy efficiency and their interactions can be extremely difficult. To understand trends in energy intensity, as shown in Figure 14, it is important to analyze the structure of the industrial sector. Industrial energy use can be broken down into that of the energy-intensive industries (e.g. primary metals, pulp and paper, primary chemicals, oil refining, building materials) and the non-energy intensive industries (e.g. electronics and food).

Reduction of energy intensity is closely linked to the definition of structure, structural change, and efficiency improvement. Decomposition analysis is used to distinguish the effects of structural change and efficiency improvement. Structural change can be broken down into intra-sectoral (e.g. a shift towards more recycled steel), inter-sectoral (e.g. a shift from steel to aluminium within the basic metals industry). A wide body of literature describes decomposition analyses (see e.g. Schipper and Meyers, 1992; Ang, 1995), and explains the trends in energy intensities, CO_2 intensities, and efficiency improvement. Decomposition analyses of the aggregate manufacturing sector exist mainly for industrialized countries (IEA, 1997d), but also for China (Sinton and Levine, 1994), Taiwan (Ang and Pandiyan, 1997; Li et al., 1990) and selected countries including Eastern Europe (Park et al., 1993). Table 9 summarizes the results of selected decomposition analyses.

Figure 14. Industrial Sector Economic Energy Intensity Trends in Selected Industrialized Countries, 1970-1995. Reference: LBNL, 1998a.

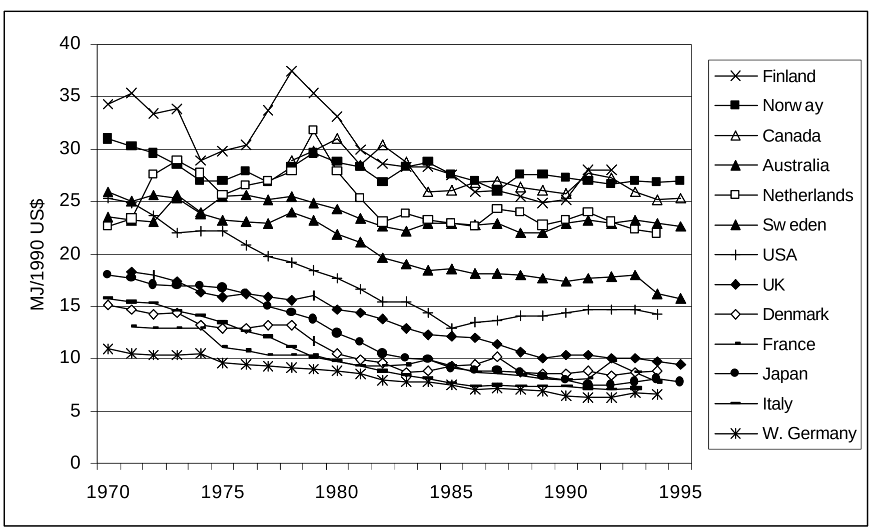


Table 9. Overview of the Results of Selected Decomposition Analyses of Manufacturing Energy Use.

Country (and period of analysis)	Annual change in aggregate energy intensity (% per year)	Contribution of structural change (% per year)	Contribution of energy intensity improvement (% per year)	References
Brazil (1973-80)	1.4%			1
Brazil (1980-88)	4.0%			1
China (1981-84)	-3.7%	-0.6%	-3.1%	2
China (1985-90)	-5.6%	-0.6%	-4.8%	2
China (1980-91)	-7.2%	-0.5%	-6.6%	3
France (1973-87)	-3.1%	-0.5%	-2.5%	4
West Germany (1973-87)	-2.6%	-0.4%	-2.2%	4
Japan (1973-87)	-4.2%	-0.9%	-3.2%	4
South Korea (1981-93)	-2.7%	-0.6%	-2.1%	3
Sweden (1973-87)	-2.2%	-0.5%	-1.7%	4
Taiwan (1980-93)	-1.4%	0.0%	-1.3%	3
Taiwan (1971-85)	-1.5%	-1.4%	-0.1%	5
United Kingdom (1973-87)	-2.4%	-0.1%	-2.3%	4
United States (1973-87)	-4.0%	-1.1%	-2.9%	4
USSR (1973-80)	-1.4%			1
USSR (1980-87)	-1.4%			1

Note: Annual trends in aggregate energy intensity are decomposed into structural change (change in the activity mix of the manufacturing sector) and energy intensity (change in energy input per unit of output for each of the sub-sectors). Note that different methodologies, analysis periods, and aggregation levels have been used, which leads to different results.

References:

1. Park et al., 1993	4. Howarth et al., 1991
2. Sinton & Levine, 1994	5. Li et al., 1990
3. Ang & Pandiyan, 1997	

The annual change in energy intensity in the industrial sector in the studies summarized in Table 9 varied between –0.1% and –6.6% per year. Generally, electricity intensity has remained constant, while fuel intensity has declined, reflecting the increasing importance of electricity (IEA, 1997d). The results also clearly show that different patterns exist for various countries, which may be due to specific conditions as well as differences in driving forces such as energy prices and other policies in these countries (IEA, 1997d). More detailed analyses on the sub-sector level are needed to understand these trends better, as well as their implications for bottom-up modeling.

Changes in energy intensities can also be disaggregated into structural changes and efficiency improvements at the sub-sector level. In the iron and steel industry, energy intensity is influenced by the raw materials used (i.e. iron ore, scrap) and the products produced (e.g. slabs, or thin rolled sheets). A recent study on the iron and steel industry used physical indicators for production, distinguished six products to describe structure, and decomposed trends in seven countries which together produced almost half of the world's steel (Worrell et al., 1997b). Figure 15 shows the trends in physical energy intensity in these countries, expressed as primary energy used per tonne of crude steel. The large differences in intensity among the countries are clearly shown, as well as the trends towards reduced intensity in most countries.

Table 10 shows the results of the decomposition analysis for the seven countries for the period 1980 to 1991. Although the analysis covered only a relatively short period, it clearly shows the differences in processes (structural changes, efficiency improvement) underlying the energy intensity trend. Actual rates of energy efficiency improvement varied between 0.0% and 1.8% per year, while in the case of the restructuring economy of Poland the energy efficiency was reduced.

Figure 15. Trends in Physical Energy Intensity (GJ/tonne crude steel) in Seven Countries Between 1971 and 1994. Reference: Worrell et al., 1997b.

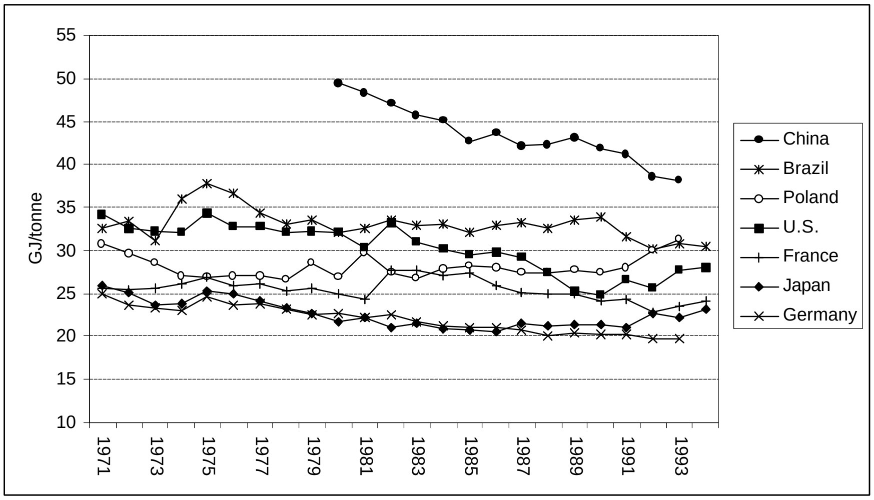


Table 10. Changes in Physical Energy Intensity (GJ/tonne of crude steel) in Seven Countries Between 1980 and 1991 and Breakdown of Structure and Efficiency Contributions to the Changes (Relative Changes in Percents). Source: Worrell et al., 1997b.

	Physical Energy Intensity 1980 (GJ/tonne)	Structure (GJ/tonne)	Efficiency (GJ/tonne)	Physical Energy Intensity 1991 (GJ/tonne)
Brazil	31.2	0.1 (+0%)	-1.6 (-5%)	29.7 (-5%)
China	51.3	0.2 (+0%)	-9.0 (-18%)	42.4 (-17%)
France	24.9	-1.8 (-7%)	1.1 (4%)	24.2 (-3%)
Germany	22.6	-0.3 (-1%)	-4.0 (-18%)	18.3 (-19%)
Japan	21.7	-0.6 (-3%)	-0.1 (-0%)	21.0 (-3%)
Poland	26.9	-0.7 (-3%)	1.8 (7%)	28.0 (4%)
U.S.	32.0	-2.1 (-6%)	-3.4 (-11%)	26.5 (-17%)

Note: The figures are based on an electricity generation efficiency of 33% across countries for all years.

4.3.2 Buildings Sector Energy Intensity Trends

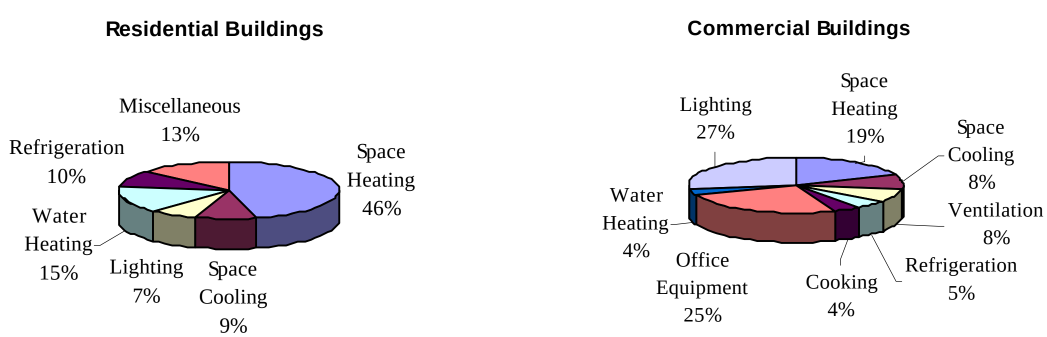
Energy is used in buildings to provide many different services, which vary widely across regions and climates. Space heating accounts for a significant share of residential buildings energy use (see Figure 16 for the U.S.), while water heating, refrigeration, space cooling, and lighting are also important. In commercial buildings, other end-uses such as office equipment and lighting dominate. The amount of energy consumed in buildings is dependent on climate, building construction, appliances and equipment within the buildings, and energy use patterns of building occupants.

Overall energy intensity in the buildings sector can be measured using energy consumption per capita values. Between 1971 and 1990, global primary energy use per capita in the buildings sector grew from 16.5 GJ/capita to 20 GJ/capita. Figure 17 shows that buildings per capita energy use varied widely by region, with the industrialized and EIT regions dominating globally. Energy use per capita is higher in the residential sector than in the commercial sector in all regions, although average annual growth in commercial energy use per capita was higher during the period, averaging 1.7% per year globally compared to 0.6% per year for the residential sector.

While informative for making general comparisons, energy consumption per capita values do not adequately describe the actual energy intensity trends within buildings. Another means of measuring these trends is to calculate energy use per unit of building floor area. This measurement, however, best reflects space heating and cooling intensities, but does not provide adequate information regarding the energy use of equipment and appliances within the buildings. Thus, a meaningful understanding of buildings energy use trends requires disaggregation of this sector into residential and commercial buildings intensity trends in space conditioning as well as in equipment and appliances within the buildings.

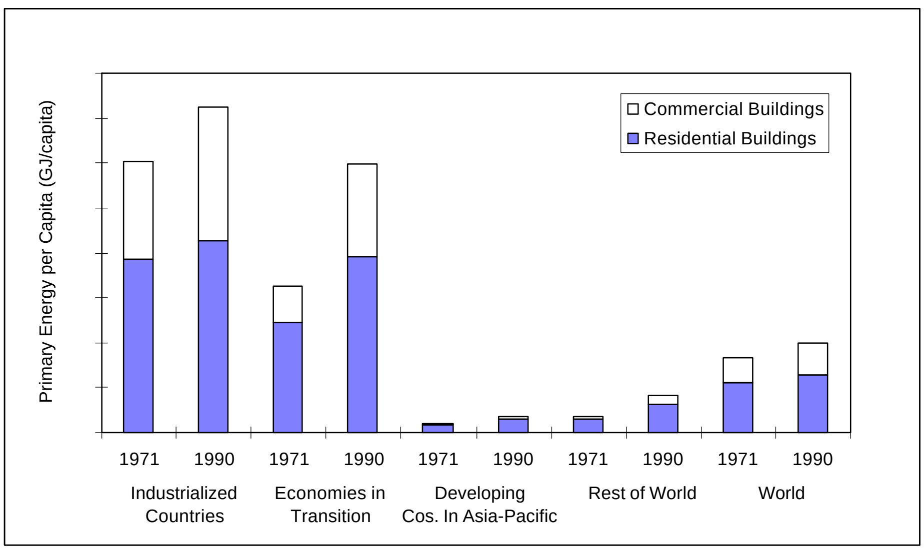
Figure 16. Buildings Primary Energy End-Uses in the United States. References: U.S. Congress, OTA, 1992; IPCC, 1995.

4.3.2.1 Residential Buildings



Energy intensity trends in residential space conditioning are affected by climate, building thermal integrity, and the heating and cooling equipment used. Space heating is an important end-use in the industrialized countries, the EIT region and in some developing countries, including half of China's residential and commercial buildings (Nadel et al., 1997). Buildings that are centrally heated consume almost twice as much energy as those that are heated by small room heaters. The penetration of central heating doubled from about 40% of dwellings to almost 80% of dwellings in many industrialized countries between 1970 and 1992 (IEA, 1997d). District heating systems are common in some areas of Europe and in the EIT region. In the former Soviet Union, district heating provides about 40% of residential space heating, with the remainder of the demand met through the use of small coal-fired boilers (U.S. Congress, OTA, 1993). Energy use for residential space heating is estimated to be about 80% of final energy use in Poland and about 75% of final energy use in the Czech Republic and the former Soviet Union (Meyers et al., 1995). Space heating is not common in most developing countries, with the exception of China, Korea, Argentina, and a few other South American countries (Sathaye et al., 1989). In China, 75% of the residential buildings that require heating use coal-fired stoves to burn raw coal, coal cakes, briquettes, or biomass (Nadel et al., 1997). Figure 18 shows that residential space heating energy intensities[13] declined in most industrialized countries (except Japan) between 1970 and 1992. Most of the decline was due to reduced heat losses in buildings, while a small portion of the savings were due to lowered indoor temperatures, more careful heating practices, and improvements in efficiency of heating equipment (IEA, 1997d; Schipper et al., 1996).

Figure 17. Primary Energy Use per Capita in Residential and Commercial Buildings by Region, 1971 and 1990. References: IEA, 1997a; IEA, 1997b, UN, 1996.



[13] Space heating energy intensities are measured as useful energy per square meter, climate corrected. Useful energy is based on the aggregates of various energy carriers, assuming that liquids and gases are converted to heat, hot water, or cooking services at 66% efficiency and solids at 55% (IEA, 1997d). Japan's space heating intensity is low due to a combination of low heating temperatures, fewer heating hours than the number of degree days implies, and a lower degree day base.

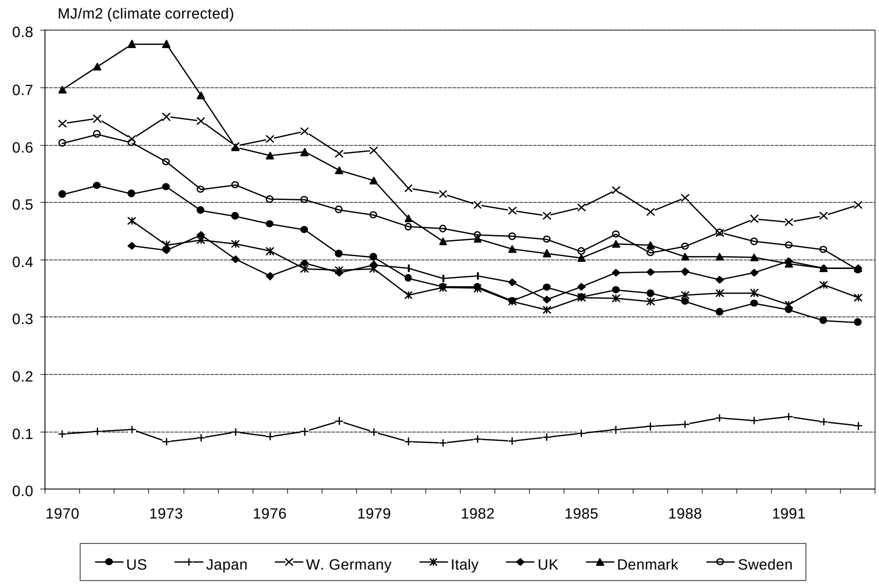


Figure 18. Residential Space Heating Energy Intensity for Selected Industrialized Countries, 1970-1993. Reference: IEA, 1997d.

Water heating, refrigeration, space cooling, and lighting, are the next largest residential energy uses, respectively, in most industrialized countries (IEA, 1997d). In developing countries, cooking and water heating dominate, followed by lighting, small appliances, and refrigerators (Sathaye and Ketoff, 1991). Appliance penetration rates increased in all regions between 1970 and 1990. Table 11 shows the growth in refrigerator and air conditioning equipment penetration rates for a number of industrialized countries during this period. In 1990, refrigerators were found in almost all households in France, Germany, Italy, Japan, and the U.S. (LBNL, 1998a). (Penetration rates over 100% indicate that more than one unit is owned per household.) Refrigerators were found in 22% of urban residences in India (1993), 66% of urban residences in China (1995), and 87% of urban residences in Thailand (1993). Air conditioners were found in 8% and 58% of urban households in China and Thailand, respectively, those years (Turiel et al., 1998). Figure 19 shows historical appliance penetration rates in urban and rural China for 1981 to 1996 (State Statistical Bureau of China, 1996).

The energy intensity of new appliances has declined over the past two decades; new refrigerators in the U.S. were 65% less energy-intensive in 1993 than in 1972. Table 12 shows energy intensity reductions in new refrigerators, freezers, clothes washers, dishwashers, and air conditioners in Denmark, former West Germany, and the U.S. (IEA, 1997d). The decline in new appliance intensities does not always mean a reduction of the average energy intensity of the appliance stock in a given country due to other factors such as stock turnover rates, appliance lifetimes, and consumer choice. Table 13 gives unit energy consumption values for selected appliance stocks in 1970 and 1990 for France, Germany, Japan, and the U.S. The increase in refrigerator intensities seen in France, Germany, and Japan was due to purchases of larger refrigerators with more features (e.g. ice makers) during this period. The average volume of refrigerators in Japan more than doubled between 1973 and 1990, offsetting reductions in energy intensity (Schipper et al., 1996).

Table 11. Refrigerator and Air Conditioner Penetration Rates in Selected Industrialized Countries, 1970 and 1990. Reference: LBNL, 1998a (France is 1972).

Refrigerator Penetration (%)	France	Germany	Italy	Japan	U.S.
1970	80	85	79	95	93
1990	98	127	96	116	118
Air Conditioner Penetration (%)					
1970	n.a.	n.a.	40	7	40
1990	n.a.	n.a.	140	114	69

Table 12. Reduction in Energy Intensity of New Appliances in Selected Industrialized Countries.* Reference: IEA, 1997d.

	Refrigerator	Freezer	Clothes Washer	Dish Washer	Base Year, Final Year
Denmark	29/51	40	35	55	1970, 1994
former W. Germany	21	37	18	29	1978,1985
U.S.	65	58	38	36	1972, 1993

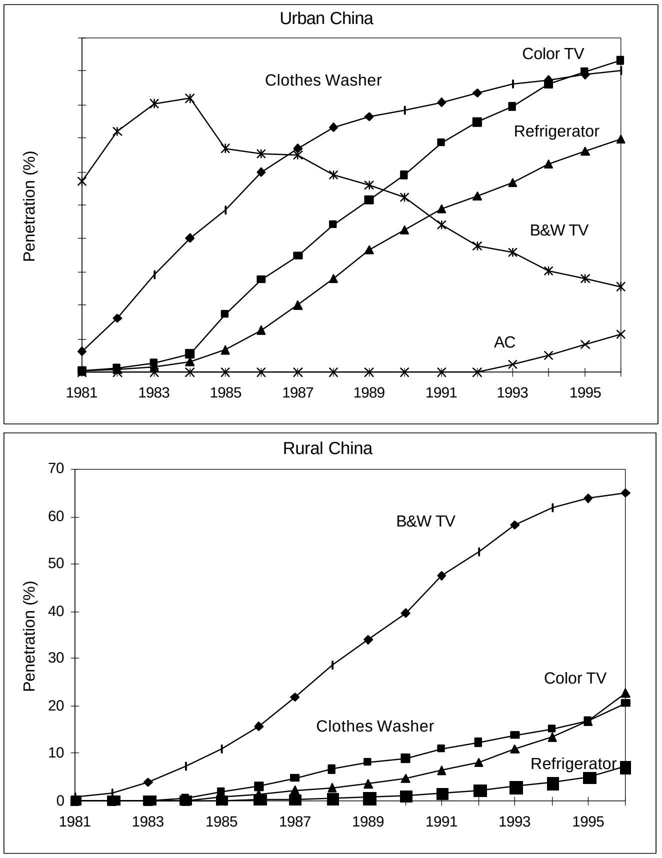
*measured as the ratio of new appliance electricity use in a recent year to that of an earlier base year.

Note: Second value for refrigerator in Denmark is for a combined refrigerator/freezer; value for refrigerator in U.S. is for a combined refrigerator/freezer.

Table 13. Unit Energy Consumption (kWh/year) for Selected Appliances in 1970 and 1990 in France, Germany, Japan, and U.S. Reference: LBNL, 1998a.

	France			Germany			Japan			U.S.		
	1970	1990	AAGR	1970	1990	AAGR	1970	1990	AAGR	1970	1990	AAGR
Refrigerators	494	630	1.2%	300	398	1.4%	283	715	4.7%	1316	1115	-0.6%
Freezer	739	690	-0.3%	700	540	-1.3%	na	na	na	1430	1039	-1.6%
Clothes Washer	366	305	-0.9%	60	51	-0.8%	28	44	2.3%	102	103	0.0%
Clothes Dryer	na	na	na	400	330	-1.0%	na	459	na	1006	952	-0.3%
Dishwasher	385	324	-0.9%	100	62	-2.4%	na	na	na	346	116	-3.6%
Air Conditioner	na	na	na	na	na	na	338	243	-1.6%	1924	1748	-0.5%

Figure 19. Appliance Penetration Rates in China, 1981 to 1996. Reference: State Statistical Bureau of China, 1996.



4.3.2.2 Commercial Buildings

Like residential buildings, energy intensity of commercial buildings is dependent upon both the building construction as well as the energy-using activities within the building. The type of building occupant clearly influences commercial buildings energy use because some buildings, such as hospitals and hotels, use energy continuously while others range from sporatic use (sports and entertainment facilities) to steady weekly use (office buildings) (IEA, 1997d). In the U.S. 15% of commercial floor space is used continuously and slightly over 35% is used less than 50 hours per week (U.S. DOE, EIA, 1992; U.S. DOE, EIA, 1994).

Primary energy use per square meter of commercial sector floor area has gradually declined in most industrialized countries despite two countervailing trends: growth in the share of electricity and increases in electricity intensity (see Figure 20) and reduction in fuel use and fuel intensity (see Figure 21). Electricity use and intensity (MJ/m^2) increased rapidly in the commercial buildings sector as penetration of computers, other office equipment, air conditioning, and lighting has grown. Fuel intensity (PJ/m^2) declined rapidly in industrialized countries as the share of energy used for space heating in commercial buildings dropped due to thermal improvements in buildings (Krackeler et al., 1998).

Figure 20. Electricity Use per Commercial Buildings Floor Area in Selected Industrialized Countries, 1970-1995. Reference: Krackeler et al., 1998.

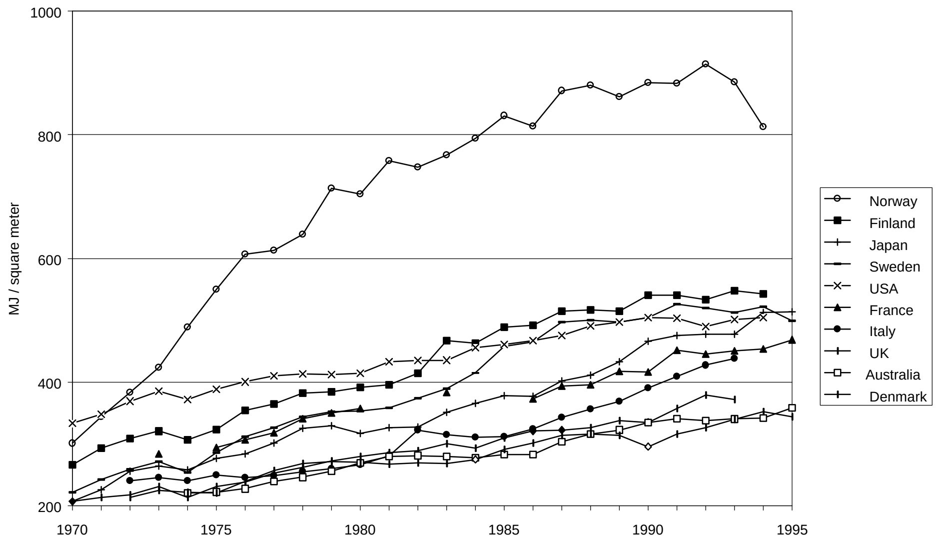
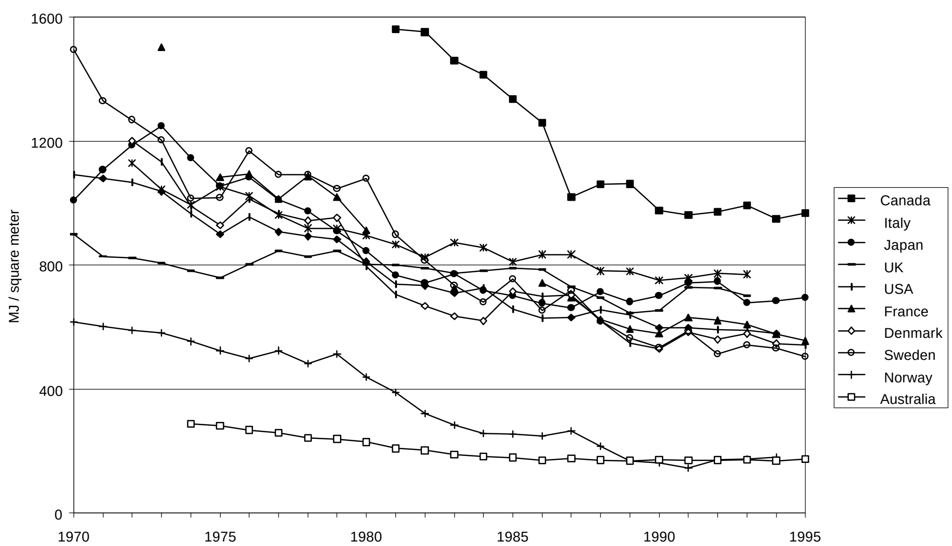


Figure 21. Fuel Use per Commercial Buildings Floor Area in Selected Industrialized Countries, 1970-1995. Reference: Krackeler et al., 1998.



4.3.3 Transport Sector Energy Intensity Trends

Energy intensity in the transport sector is measured as energy used per passenger-km for passenger transport and per tonne-km for freight transport. Table 14 gives 1990 energy intensities and historical intensity reduction trends for a range of transport modes in a small sample of countries. Transport energy projections typically incorporate a reduction in fleet energy intensity in the range 0.5% to 2% per year (Grübler et al., 1993; IEA, 1993; Walsh, 1993), but even the lower end of this range may be optimistic for the future.

Table 14. Trends in Transport Energy Intensity in Selected Countries. Reference: Michaelis et al., 1996.

Mode	National Average 1990 Energy Intensity (MJ/pass-km or MJ/ tonne-km)	Historical Trend in Energy Intensity (Annual % Reduction 1985-1995)
Cars	1.2 - 3.1	0 to 1.0
Average Road Freight	1.8 - 4.5	0.3 to 0.6
Heavy Trucks	0.6 -1.0	0 to 0.6
Freight Trains	0.4 - 1.0	0 to 0.3
Aviation	1.5 - 2.5	0.4-0.8

Passenger transport energy intensity varies widely depending upon the mode of transport (see Table 15). On-road energy intensity (fuel consumption per kilometre driven) of light-duty passenger vehicles in North America fell by nearly 2% per year between 1970 and 1990, to about 13 to 14 litres per 100 kilometers, but is now stationary or rising. The current average on-road energy intensity in North America is 25-30% higher than that in Europe (Schipper, 1996). In other industrialized countries, changes in on-road fuel consumption from 1970 to the present were quite small. Whereas on-road average energy intensity fell only slightly in Europe and Japan during the last 20 years, new car fuel consumption according to official tests fell by about 20% (IEA, 1993, Schipper, 1996). The divergence between these two measures has been widely reported and is growing in many countries (IEA, 1993; Martin and Shock, 1989; Schipper and Tax, 1994). Differences arise because, *inter alia*, the tests do not adequately reflect changing traffic conditions; cars are not usually tested with auxiliary equipment, such as air conditioning, in operation; and some tests do not include cold starts, which can result in excess fuel consumption as high as 50% for short trips in cold weather (Hausberger et al., 1994).

Even in some countries such as Italy and France, where fleet average energy intensity has fallen during the past 20 years, the energy intensity of car travel (MJ/passenger-km) has increased as a result of declining car occupancy (Schipper et al., 1993). Meanwhile, the more recent trend is towards higher energy intensity in new cars, in countries including the United States, Germany, and Japan (IEA, 1993). The implication is that without changes in government policy, light duty vehicle energy intensity cannot be expected to fall in the near future, although a reduction of up to 0.5% per year is possible. Factors in the recent increases in energy intensity include the trend towards larger cars, increasing engine size, and the use of increasingly power-hungry accessories (IEA, 1993; Martin and Shock, 1989; Difiglio et al., 1990; Greene and Duleep, 1993). The range of vehicle types used for personal transport has also expanded, with a growing market for "light trucks" (small pickup trucks and minibuses) and in particular towards the new classes of sport utility vehicles and the growing use of four- and all-wheel drive options.

Table 15. Passenger Transport Energy Intensity: Estimated National Averages. References: Chin and Ang, 1994; Davis and Strang, 1993; Faiz, 1993; Grübler et al., 1993; CEC, 1992; Schipper et al., 1993; Walsh, 1993.

	Light Duty Passenger Vehicles	Mopeds	Buses	Trains†
Country/date of estimate	MJ/pass-km	MJ/pass-km	MJ/pass-km	MJ/pass-km
Sub-Saharan Africa, 1985	3.2-3.8		0.2-0.33	
China, India, Thailand, c. 1990	1.8-2	0.5-0.8	0.35	
Singapore, 1992	1.7	0.7	0.6	1.2
Japan, Korea, 1991	1.5-1.6	0.7-0.8	0.65	0.55
United States, 1991	2.6		0.9	2.75-3.0
W. Europe, 1991	1.2-1.96	0.7-0.8	0.49-1.32	0.75-2.8
Poland, 1991	1.3	0.73	0.33	0.32-0.83
Former USSR, 1988	2		0.6	

† Electricity as primary: efficiency of conversion from primary energy to electricity supplied to locomotives assumed to be 30%.

Average truck energy use per tonne-kilometre of freight moved has shown little sign of reduction during the past 20 years in countries where data are available (Schipper et al., 1993). These data are difficult to obtain and interpret in most countries, partly because of the wide variety of vehicle types that carry freight by road, and differences among countries in the way in which goods transported by these vehicles are included in national statistics.

Energy use is typically in the region of 0.7 to 1.4 MJ/tonne-km for the heaviest trucks but can be in excess of 5 MJ/tonne-km for smaller trucks. In countries where services and light industry are growing faster than heavy industry, the share of small trucks or vans in road freight is increasing. Along with the increasing power-to-weight ratios of goods vehicles, these trends offset, and in some cases outweigh, the benefits of improving engine and vehicle technology (Delsey, 1991). Energy intensity tends to be lower in countries with large heavy-industry sectors, because a high proportion of goods traffic is made up of bulk materials or primary commodities.

Over the 30 years to 1990, the average energy intensity (civil aviation energy use[14] per tonne-km of passengers, freight and mail carried) of the civil aircraft fleet fell by about 2.7% per year. The fastest reduction, of about 4% per year, was in the period 1974 to 1988. For comparison, energy intensity in cars over the same period fell by 1-2% per year, depending on the region. The large reductions in energy intensity during the 1970s and 1980s resulted partly from developments in the technology used for new aircraft in the rapidly expanding civil aircraft fleet and partly from increases in aircraft load factor (passengers per seat or percentage of cargo capacity filled). The aircraft weight load factor increased from 49% in 1972 to 59% in 1990, but nearly all of this rise occurred during the 1970s (ICAO, 1995a, 1995b). Operational changes (advances in routing and navigation, introduction of energy-conserving practices) may also have accounted for additional savings, but the bulk of the reduction in energy intensity since 1960 has been through aircraft technology development.

4.4 Carbon Intensity Trends

Carbon intensity changes mainly as a result of fuel substitution, but also as a result of changes in technology or process in the energy supply chain. Thus, the largest shifts in carbon intensity have been associated with changes in the energy sources used for power generation (Nakicenovic and Grübler, 1996). Smaller shifts have resulted from fuel switching in industrial, commercial and residential energy consumption.

4.4.1 Industrial Sector Carbon Intensity Trends

In industry, changes in carbon intensity and elasticity depend strongly on the sub-sector and its potential for fuel switching and efficiency improvement. For example, the use of biomass is historically connected with the forest products and food industries (e.g. bagasse in sugar making). New technologies and policies could make biomass use in other industrial sectors more economically attractive. Industries that use a large share of energy in biolers can convert to other fuels more easily than others. The growing market share of industrial cogeneration using relatively cheap gas turbine technologies is an example of a technology pushing the shift towards lower carbon fuels.

CO_2 emissions as a function of GDP of the industrial sector appear to stabilize in most countries, except for rapidly industrializing countries (IPCC, 1995). This trend is the result of changing economic structure, improved energy efficiency, and reduced carbon intensity of the fuel mix. A shift towards less carbon-intensive fuels took place between 1971 and 1992 in most industrialized countries as well as in S. Korea (Schipper et al., 1997a; Ang and Pandiyan, 1997). The fuel mix has become more carbon-intensive in some developing countries such as China and Mexico (Ang and Pandiyan, 1997; Sheinbaum and Rodiguez, 1997), although a trend away from coal to other fuels has also been seen in some developing countries (Han and Chatterjee, 1997). The contribution of fuel mix changes to CO_2 emissions reduction has been small in most industrialized countries (Schipper et al., 1997a; Golove and Schipper, 1997). Electrification has grown in all sectors in almost all countries (Han and

[14] Aviation energy use is estimated using a) equations derived from publicly available data that estimate fuel consumption for individual aircraft types; and b) scheduled airline timetables. Thus, it takes no account of changes in operational influences on energy use, such as air traffic congestion and changes in airline operating practices. The estimate does take account of changes in aircraft load factor.

Chatterjee, 1997). However, the effect of increasing electrification on industrial emissions is unclear (IPCC, 1995). Price differences and elasticities, as well as lifetimes of existing process equipment, will influence future trends in fuel mix.

Various authors have studied the changes in fuel mix and effects on total CO_2 emissions of the manufacturing industry in industrialized countries (Torvanger, 1991; Schipper et al., 1997a), China, South Korea, Taiwan (Ang and Pandiyan, 1997), and Mexico (Sheinbaum and Rodiquez, 1997). Although there has been a general overall trend towards lower carbon intensity (IPCC, 1992), Table 16 shows that fuel mix changes towards more carbon-intensive fuels occurred in industry in various countries. Such shifts may be related to availability of resources, policy measures, or change in the intra-sectoral structure.

Table 16. Annual Changes in Fuel Mix and Carbon Intensity in the Manufacturing Industry in Various Countries.

Country	Annual change in fuel mix (% per year)	Annual change in overall carbon intensity (% per year)	References
China (1980-91)	+0.4%	-0.2%	Ang & Pandiyan,1997
Denmark (1973-91)	+0.6%	-1.2%	Schipper et al., 1997a
Finland (1973-91)	-2.1%	-3.9%	Schipper et al., 1997a
France (1973-91)	+0.2%	-2.3%	Schipper et al., 1997a
West Germany (1973-91)	+0.7%	-2.5%	Schipper et al., 1997a
Italy (1973-91)	+0.2%	-3.1%	Schipper et al., 1997a
Japan (1973-91)	+0.6%	-4.0%	Schipper et al., 1997a
Japan (1979-87)	+0.3%	-0.8%	Torvanger, 1991
Mexico (1987-93)	+0.7%	-2.5%	Sheinbaum & Rodriquez, 1997
Norway (1973-91)	-2.8%	-3.9%	Schipper et al., 1997a
South Korea (1981-93)	+0.2%	-0.9%	Ang & Pandiyan, 1997
Sweden (1973-91)	-1.7%	-6.3%	Schipper et al., 1997a
Taiwan (1980-93)	+0.3%	-0.2%	Ang & Pandiyan, 1997
United Kingdom (1973-91)	+0.9%	-2.3%	Schipper et al., 1997a
United States (1973-91)	+0.3%	-2.4%	Schipper et al., 1997a
United States (1979-97)	+0.3%	-0.2%	Torvanger, 1991

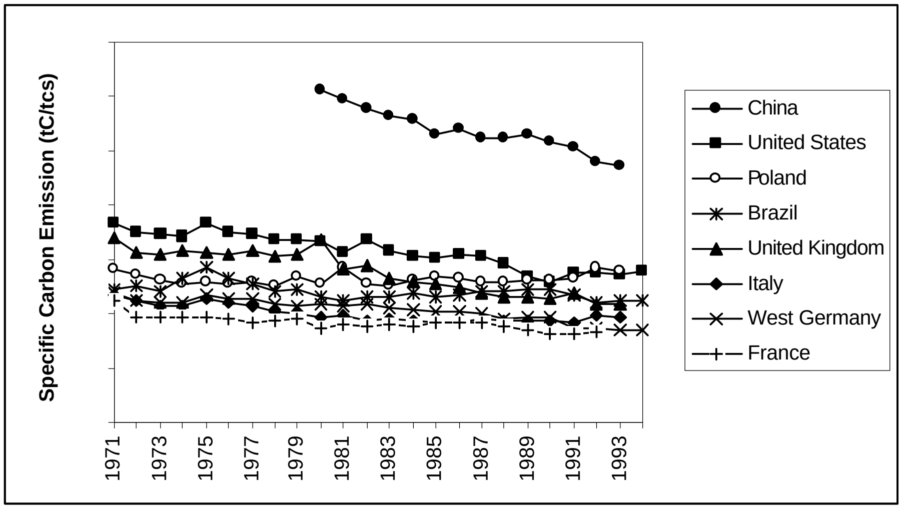
Note: The changes in fuel mix represent the change in carbon emissions through a change in the final fuel mix of the power sector. The changes in carbon intensity represent the total changes in the energy consumed by industry, and is the product of changes in energy intensity, fuel mix, and fuel mix of the utilities.

In the iron and steel industry energy is used primarily for the reduction of iron oxides. The dominant process has been, and most likely will remain, the blast furnace, that uses coke as the primary reduction agent. Early blast furnaces, as well as some newly designed Brazilian blast furnaces, used charcoal as the reduction agent, requiring large quantities of wood. Later in the 19th century, coke (from coal) proved to be a much better reductant in British blast furnaces. Today, coke is the dominant fuel, partially replaced by injected fuels (coal, oil, gas). New technologies make it possible to replace coke completely by other fuels including coal and natural gas. These technologies currently have only a very small share of the global iron production.

Energy use for the production of steel is reduced by changes in efficiency and increased use of secondary materials. This trend, although not observed in all countries, also leads to a relatively small change in fuel-mix, away from coal towards more electricity and other (gaseous) fuels.[15] This leads to a reduction of the direct carbon emissions from the iron and steel industry. These may partly be offset by the emissions of the power sector, if fossil fuels are used for power generation. Figure 22 depicts the trends in specific carbon emissions for major steel producing countries around the world and shows a declining carbon intensity of steelmaking in nearly all countries. The countries with relative low carbon intensities are those countries with a high share of secondary steelmaking (e.g. Italy), energy efficient practices (e.g. West Germany) or use of low carbon energy sources in steelmaking (e.g. Brazil) or power production (e.g. Brazil, France).

[15] Special circumstances, i.e. in Brazil, may lead to a different trend as non-fossil fuels are used in the reduction of iron oxides.

Figure 22. Trends in Specific Carbon Emissions for the Production of Crude Steel in Major Steel Producing Countries for the Period 1971-1994 (expressed in tonne C/tonne crude steel). References: Worrell et al., 1997b; Faaij et al., 1995.



Note: carbon emissions from power production have been held constant at 1990 level for each country.

4.4.2 Buildings Sector Carbon Intensity Trends

Carbon intensity trends can be measured as either carbon emissions per unit of primary energy or per sectoral activity measurement (e.g. per capita and per square meter of floor area). Measuring carbon per unit of primary energy provides an indication of trends in the fuel mix, tracking whether more or less carbon-intensive fuels are being used to provide energy to buildings. Figure 23 shows that carbon intensity of the residential sector declined in most industrialized countries between 1970 and the early 1990s (LBNL, 1998a). In the commercial sector, carbon dioxide emissions per meter of commercial floor area also dropped in most industrialized countries during this period (see Figure 24) even though carbon intensity for electric end-uses (kgC from electricity/m^2) increased in most industrialized countries, dropping only in France, Sweden, and Norway, countries that moved away from fossil fuels (Krackeler et al., 1998).

In developing countries, biomass is often used in the residential sector, especially in rural areas. Increased urbanization, as well as increasing incomes and rural electrification, lead to rising carbon intensities in buildings because the mostly sustainable biomass is replaced with carbon-intensive fuels such as liquified petroleum gas (LPG), coal, and electricity generated by fossil fuels. In Brazil, the share of biomass energy used in the residential sector dropped from 90% in 1971 to just over 50% in 1992 as urban populations grew. In India, increasing incomes translated into replacement of biomass first with kerosene, then LPG, and finally electricity. This trend toward replacement of biomass fuels with commercial fuels in expected to continue in developing countries (IEA, 1995).

Figure 23. Carbon Dioxide Emissions in the Residential Sector in Selected Industrialized Countries, 1970-1995. Reference: LBNL, 1998a.

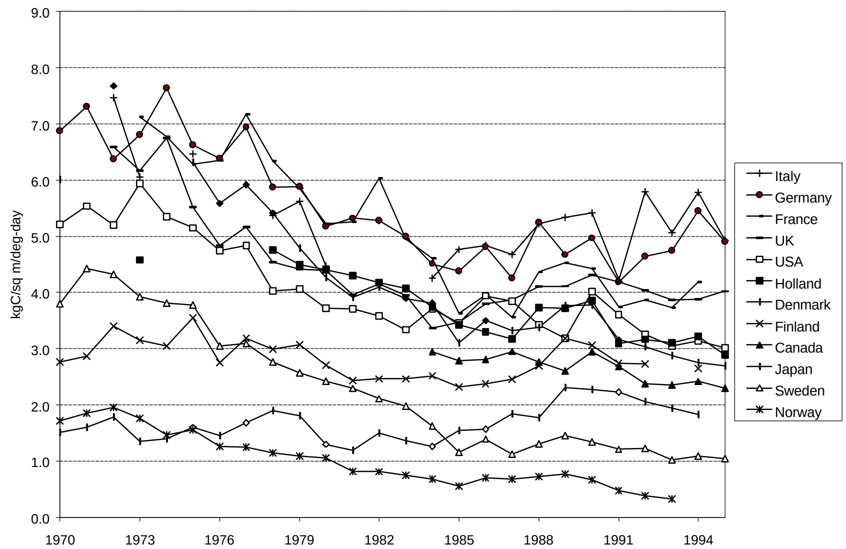
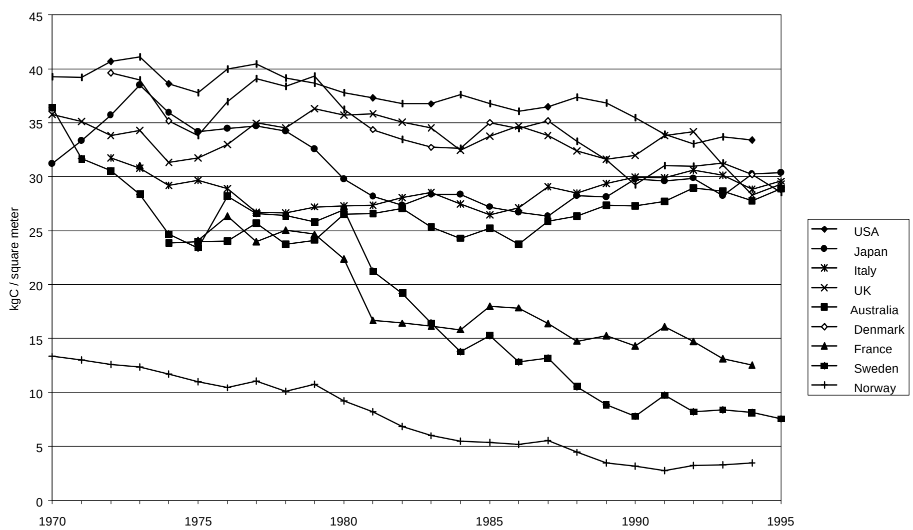


Figure 24. Carbon Emissions per Commercial Buildings Floor Area in Selected Industrialized Countries, 1970-1995. Reference: Krackeler et al., 1998.



4.4.3 Transport Sector Carbon Intensity Trends

Transport sector carbon intensities for personal travel, measured as the ratio of emissions to passenger-km travelled, increased in most European countries and Japan between 1972 and 1994 (see Table 17). This increase was the result of falling load factors (persons per vehicle) that were greater than improvements in vehicle energy intensity. The only exception among industrialized countries was the U.S., where carbon intensities dropped from 55 kgC/passenger-km in 1972 to 46 kgC/passenger-km in 1994 (IEA, 1997d; Schipper et al., 1997a). Carbon intensity of freight travel, measured as the ratio of emissions to tonne kilometers transported, rose slightly in a number of industrialized countries between 1972 and 1994, mostly due to modal shifts to more carbon-intensive trucks (Schipper et al., 1997b).

Fuels used to power transport are typically oil-based, except for rail, where shifts towards electrified systems can lower carbon intensities depending upon the source of fuel for electricity generation in the country.

In France, for example, the move toward electrified rail based on nuclear power generated electricity, lead to lower carbon intensities (IEA, 1997d). Increased use of diesel engines can reduce CO_2 emissions, but leads to greater emissions of other gaseous pollutants such as nitrous oxide and carbon monoxide. Use of alternative fuels, such as compressed natural gas, LPG, and ethanol can significantly reduce CO_2 emissions from transport (IEA, 1995). In Brazil, where there has been a major effort to use alcohol as a transportation fuel since the late 1970s, it is estimated that nearly total Brazilian CO_2 emissions from fossil fuels have been lowered by 18% over projected emissions levels without these fuels (Goldemberg and Macedo, 1994).

Table 17. Trends in Passenger and Freight Carbon Intensity in Selected Industrialized Countries, 1972 and 1994. Reference: LBNL, 1998a.

	Passenger Transport Carbon Intensity		Freight Transport Carbon Intensity (kgC/tonne kilometer)	
	1972	1994	1972	1994
Australia	40	43	17	22
Denmark	28	26	48	63
Finland	31	34	23	24
France	26	25	34	48
Germany	33	40	34	29
Italy*	26	25	39	35
Japan	22	30	45	52
The Netherlands	26	50	n.a.	37
Norway	27	27	52	32
Sweden	32	36	22	26
UK	34	33	55	49
USA	55	46	24	24

* passenger carbon intensities for Italy are for 1973, not 1972.

5. Conclusions

While the industrialized countries clearly dominate current energy use and greenhouse gas emissions, the large recent population and energy use growth patterns in many developing countries, coupled with trends in sector-specific indicators such as lower number of people per household and increased per capita vehicle ownership in these countries, clearly illustrate the potential for significant increases in energy use and greenhouse gas emissions in these areas as these countries improve their welfare levels. Analysts and policymakers interested in understanding future trends and the potential to mitigate emissions require detailed sectoral and regional information to identify appropriate measures and formulate effective policies.

Energy use and greenhouse gas emissions trends vary widely by region of the world and end-use sectors. Using various data sources and reallocation methods to improve on the IEA Energy Balances, we were able to disaggregate energy use and CO_2 emissions into the key end-use sectors of industry, transport, buildings, and agriculture and to provide historical data for these sectors both globally and regionally. Using the key elements of the Kaya formula, we discussed the driving factors underlying these historical trends, showing that many factors influence energy consumption and CO_2 emissions. The varying contribution of the different drivers regionally and over time helps to explain global and regional CO_2 emission trends. Scenarios of future energy use and greenhouse gas emissions should reflect an understanding of these historical trends and their driving forces.

Driving forces behind energy use and carbon emissions in the industrial sector include the country's state of economic development, consumption and trade patterns, relative costs of energy, and availability of resources. In the buildings sector, household expenditure levels, appliance and equipment penetration levels, and the share of population living in urban areas all affect energy use. Settlement patterns, infrastructure and social factors affect vehicle choice and kilometers traveled as much as income levels and fuel prices.

In addition, the energy intensity and other characteristics of the technologies used in each of these sectors play a role in determining the amount of energy consumed. Fuel choice, which is a key factor in determining carbon emissions, is strongly affected by local availability and non-price factors, which are difficult to take into account in models. These many influences on energy use and greenhouse gas emissions vary widely by country and region of the world, but are essential to understand the model results, and the consequences for policy making.

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Appendix A. Definition of Regions

Industrialized Countries: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, U.K., U.S.

Economies in Transition: Armenia, Azerbaijan, Belarus, Bulgaria, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldovia, Poland, Romania, Russian Federation, Slovakia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan

Developing Countries in Asia/Pacific: Afganistan, American Samoa, Bangladesh, Bhutan, Brunei, Cambodia, China, Fiji, French Polynesia, Hong Kong, India, Indonesia, Kiribati, Korea (N.), Korea (S.), Laos, Malaysia, Maldives, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papau New Guinea, Philippines, Solomon Islands, Singapore, Sri Lanka, Thailand, Vanuatu, Vietnam

Rest of World: all remaining countries

References

AAMA: 1996, *World Motor Vehicle Data, 1996 Edition*, Washington, D.C., AAMA.

Ang, B.W.: 1995, 'Decomposition Methodology in Industrial Energy Demand Analysis', *Energy* **20**(11),1081-1096.

Ang, B.W. and Pandiyan, G.: 1997, 'Decomposition of Energy-Induced CO_2 Emissions in Manufacturing' *Energy Economics* **19**, 363-374.

Armstrong, D.M.: 1993, 'Transport Infrastructure, Urban Form and Mode Usage: An Econometric Analysis Based on Aggregate Comparative Data', in *Regional Science Association Thirty Third European Congress, Moscow, 24-27 August 1993*, Belfast, N. Ireland, Northern Ireland Economic Research Centre,.

Ayres, R.U.: 1989, 'Energy Efficiency in the U.S. Economy: A New Case for Conservation', Pittsburgh, PA, Carnegie Mellon University.

Banister, D.: 1992, 'Energy Use, Transport and Settlement Patterns', *Sustainable Development and Urban Form* Breheny, MJ (ed). London, Psion.

Bennathan, E., Fraser, J. and Thompson, L.S.: 1992, *What Determines Demand for Freight Transport?* Policy Research Working Paper WPS 998. Washington, DC, World Bank.

Bernardini, O. and Galli, R.: 1993, 'Dematerialization: Long-Term Trends in the Intensity of Use of Materials and Energy', *Futures* **25**, 431-447.

BP: 1997, *BP Statistical Review of World Energy 1997*. London: BP (www.bp.com).

Bunch, D.S., Bradley, M.A., Golob, T.F., Kitamura, R. and Occhiuzzo, G.P.: 1993, 'Demand for Clean-Fuel Vehicles in California: a Discrete Choice Stated Preference Approach', *Transportation Research A* **27A**(3), 237-253.

Chin, T.H. and Ang, B.W.: 1994, 'Energy, Environment and Transport Policy in Singapore', *Sectoral Meeting on Energy, Environment and Urban Transport*, Hong Kong, UNESCAP.

Cole, V., et al.: 1996, 'Agricultural Options for Mitigation of Greenhouse Gas Emissions', *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, Cambridge, Cambridge University Press.

CEC: 1992, *Research and Technology Strategy to Help Overcome the Environmental Problems in Relation to Transport (SAST Project No. 3) Global Pollution Study*, Brussels and Luxembourg, CEC Directorate-General for Science, Research and Development.

Dahl, C. and Sterner, T.: 1991, 'A Survey of Econometric Gasoline Demand *International Journal of Energy Systems*, **11**(2).

Davis, S.C. and Strang, S.G.: 1993, *Transportation Energy Data Book: Edition 13*. Oak Ridge, Tennessee, Oak Ridge National Laboratory.

Delsey, J.: 1991, 'How to Reduce Fuel Consumption of Road Vehicles', *Low Consumption/Low Emission Automobile*. Proceedings of an Expert Panel. Paris, OECD.

Dietz, T. and Stern, P.C.: 1993, *Individual Preferences, Contingent Valuation, and the Legitimation of Social Choice*. Draft report. Washington, DC, National Research Council.

Difiglio, C., Duleep, K.G., and Greene, D.L.: 1990, 'Cost Effectiveness of Future Fuel Economy Improvements', *The Energy Journal*, **11**(1).

DRI/McGraw-Hill: 1997, 'Transportation Sector Subsidies: U.S. Case Study', *Environmental Implications of Energy and Transport Subsidies. Volume 3, Supports to the Road Transport Sector*. Paris: OECD (OCDE/GD(97)156).

Ellis, J. and Tréanton, K.: 1998, 'Recent Trends in Energy-Related CO_2 Emissions', *Energy Policy* **26**(3), 159-166.

Evans, M.: 1996, 'Modelling Steel Demand in the UK', *Ironmaking and Steelmaking* **23**(1),17-24.

Faaij, A.P.C., Blok, K. and Worrell, E.: 1995, 'World-wide Comparison of Efficiency and Carbon Dioxide Emissions of Public Electricity Generation', Utrecht, The Netherlands, Department of Science, Technology & Society, Utrecht University.

Faiz, A.: 1993, 'Automotive Emissions in Developing Countries — Relative Implications for Global Warming, *Transportation Research-A*, **27A**(3), 167-186.

Fowkes, A.S., Nash, C.A., Toner, J.P., and Tweddle, G.: 1993, *Disaggregated Approaches to Freight Analysis: A Feasibility Study*, Working Paper 399, UK, Institute of Transportation Studies, University of Leeds.

Freeman, S.L., Niefer, M.J., Roop, J.: 1996. *Measuring Industrial Energy Efficiency: Physical Volume Versus Economic Value*. Richland, WA: Pacific Northwest National Laboratory.

Goldemberg, J. and Macedo, I.C.: 1994. 'Brazilian Alcohol Program: An Overview', *Energy for Sustainable Development*, 1(1), 17-22.

Golove, W. and Schipper, L.: 1997, 'Restraining Carbon Emissions: Measuring Energy Use and Efficiency in the *Energy Policy* **25**(7-9), 803-812.

Goodwin, P.B.: 1992, 'A Review of New Demand Elasticities with Special Reference to Short and Long Run Effects of Price Changes', *Journal of Transport Economics and Policy*, **26**(2), 155-170.

Greene, D.L.: 1992, 'Vehicle Use and Fuel Economy: How Big is the "Rebound" Effect?' *The Energy Journal* **13**(1), 117-143.

Greene, D.L. and Duleep, K.G.: 1993, 'Costs and Benefits of Automotive Fuel Economy Improvement: A Partial *Transportation. Research-A*, 27A (3), 217-235.

Greening, L.A. and Jeng, H.T.: 1994, 'Life-Cycle Analysis of Gasoline Expenditure Patterns'. *Energy Economics* **16**(3), 217-228.

Greening, L.A., Jeng, H.T., Formby, J. and Cheng, D.C.: 1994, 'Use of Region, Life-Cycle and Role Variables in the Short-Run Estimation of the Demand for Gasoline and Miles Travelled', *Applied Economics* **27**(7), 643-655.

Grübler, A., Messner, S., Schrattenholzer, L. and Schäfer, A.: 1993, 'Emission Reduction at the Global Level', *Energy* **18**(5), 539-581.

Han, X. and Chatterjee, L.: 1997, 'Impacts of Growth and Structural Change on CO_2 Emissions of Developing Countries', *World Development* **5**(2), 395-407.

Hausberger et al.: 1994, *KEMIS — A Computer Program for the Simulation of on-Road Emissions Based on the Characteristical Driving Behaviour*. Graz, Austria, Institute for Internal Combustion Engines and Thermodynamics, Technical University.

Hausberger, S.: 1996, Personal communication. Graz, Austria, Technical University.

Hensher, D.A., Milthorpe, F.W., and Smith, N.C.: 1990, 'The Demand for Vehicle Use in the Urban Household Sector: Theory and Empirical Evidence', *Journal of Transport Economics and Policy,* **24**(2),119-137.

Howarth, R.B., Schipper, L., Duerr, P.A., and Strom, S.: 1991, 'Manufacturing Energy Use in Eight OECD Countries, Decomposing the Impacts of Changes in Output, Industry Structure and Energy Intensity' Energy Economics **13**, 135-142.

Intergovernmental Panel on Climate Change: 1992, *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment,* Cambridge, Cambridge University Press.

Intergovernmental Panel on Climate Change: 1995, *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses: Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, New York, Cambridge University Press.

ICAO: 1995a, *Outlook for Air Transport to the Year 2003,* Circular 252-AT/103, Montreal, ICAO.

ICAO: 1995b, *Civil Aviation Statistics of the World, 1994*, Doc 9180/20, Montreal, ICAO.

IEA: 1993, *Cars and Climate Change,* Paris, OECD.

IEA: 1994a, *Energy Statistics and Balances: OECD/OCDE (1960-1992); Non-OECD/Non Membres (1971-1992) – Diskette Service Documentation*. Paris: IEA/OECD.

IEA: 1994b, *World Energy Outlook, 1994 Edition,* Paris, OECD.

IEA: 1995, *World Energy Outlook, 1995 Edition,* Paris, IEA/OECD.

IEA: 1997a, *Energy Balances of OECD Countries, 1960-1995*, Paris, IEA/OECD.

IEA: 1997b, *Energy Balances of Non-OECD Countries, 1960-1995,* Paris, IEA/OECD.

IEA: 1997c, *CO_2 Emissions from Fuel Combustion: Annex II Countries 1960-1995; Non-Annex II Countries 1971-1995*, Paris, IEA/OECD.

IEA: 1997d, *Indicators of Energy Use and Efficiency: Understanding the Link Between Energy and Human Activity*, Paris, IEA/OECD.

ISII: 1996, *Steel Statistical Yearbook 1995*, Brussels, Belgium, IISI.

Jacobs, M.: 1994, 'The Limits to Neoclassicism: Towards an Institutional Environmental Economics', *Social Theory and the Global Environment*, eds. M. Redclift and T. Benton, London, Routledge.

Jänicke, M., Binder, M. and Mönch, H.: 1997, ''Dirty Industries': Patterns of Change in Industrial Countries' *Environmental Resource Economics* **9**, 467-491.

Jansson, J.O.: 1989, 'Car Demand Modelling and Forecasting', *Journal of Transport Economics and Policy* **23**(2), 125-140.

Jochem, E.: 1989, 'Rationelle Energienutzung in den Industrieländern – Praxis und Zukünftige Chancen', 53. *Physikertagung der Deutschen Physickalischen Gesellschaft*, Bonn.

Jones, C.T.: 1993, 'Another Look at U.S. Passenger Vehicle Use and the "Rebound" Effect from Improved Fuel *The Energy Journal* **14**(4), 99-143.

Kaya, Y.: 1989, *Impact of Carbon Dioxide Emissions on GNP Growth: Interpretation of Proposed Scenarios*, Geneva, Intergovernmental Panel on Climate Change, Response Strategies Working Group.

Koopman, G.J.: 1995, 'Policies to Reduce CO_2 Emissions from Cars in Europe', *Journal of Transport Economics and Policy*, January, 53-70.

Krackeler, T., Schipper, L., and Sezgen, O.: 1998, *The Dynamics of Service Sector Carbon Dioxide Emissions and the Critical Role of Electricity Use: A Comparative Analysis of 13 OECD Countries from 1973-1995*, Berkeley, CA, LBNL, (LBNL-41882).

LBNL: 1998a, *OECD Database*, Berkeley, CA, LBNL, International Energy Studies.

LBNL: 1998b, *LDC Database*, Berkeley, CA, LBNL, International Energy Studies.

Li, J.-W., Shrestha, R.M. and Foel, W.K.: 1990, 'Structural Change and Energy Use, The Case of the Manufacturing Industry in Taiwan' *Energy Economics* **12**, 109-115.

Lovins, A.B. and Lovins, L.H.: 1991, 'Least-Cost Climatic Stabilization,' *Annual Review of Energy* **16**, 433-531.

Malenbaum, W.: 1975, *World Demand for Raw Materials in 1985 and 2000*, New York, McGraw-Hill.

Mannaerts, H.: 1997, *STREAM, Economic Activity and Physical Flows in an Open Economy*, The Hague, The Netherlands Central Planning Bureau.

Martin, D.J. and Shock, R.A.W.: 1989, *Energy Use and Energy Efficiency in UK Transport up to the Year 2010*, Energy Efficiency Series No. 10, London, Energy Efficiency Office, Department of Energy HMSO.

Martin, N., Worrell, E., Schipper, L., and Blok, K.: 1995, *International Comparisons of Energy Efficiency: Workshop Proceedings, March 6-9, 1994*, Berkeley, CA, LBNL.

Maslow, A.: 1954, *Motivation and Personality*, New York, Harper and Row.

Meyers S., Khrushch, M., L'Heureux, M.A., Martinot, E., Salay, J., Schipper, L, Chyrczakowski, S., and Voracova, Z.: 1995, *The Residential Space Heating Problem in Eastern Europe: The Context for Effective Strategies*, Berkeley, CA, LBNL (LBNL-2095).

Michaelis, L.: 1997, *Special Issues in Carbon/Energy Taxation: Carbon Charges on Aviation Fuel: Policies and Measures for Common Action under the UNFCCC*, Working Paper 12, Paris, OECD.

Michaelis, L.: 1996, *CO_2 Emissions from Road Vehicles: Policies and Measures for Common Action under the UNFCCC*, Working Paper 1, Paris, OECD.

Michaelis, L. and Davidson, O.: 1996, 'GHG Mitigation in the Transport Sector', *Energy Policy* **24**(10-11).

Michaelis, L, Bleviss, D.L., Orfeuil, J-P., and Pischinger, R.: 1996, 'Mitigation Options in the Transportation *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Watson, R.T., M. C. Zinyowera, and R.H. Moss (eds.)]. Cambridge and New York, Cambridge University Press.

Mogridge, M.J.H.: 1983, *The Car Market: A Study of The Statistics and Dynamics of Supply-Demand Equilibrium*, London, Pion.

Nadel, S.M., Fridley, D., Sinton, J., Zhirong, Y., Hong, L.: 1997. *Energy Efficiency Opportunities in the Chinese Building Sector.* Washington, DC: American Council for an Energy-Efficient Economy.

Nakicenovic, N. (ed.): 1993, 'Long-Term Strategies for Mitigating Global Warming', *Energy* **8**, 401-609.

Nakicenovic, N. and Grübler, A.: 1996, 'Energy and the Protection of the Atmosphere', NY, UN Department for Policy Coordination and Sustainable Development.

Newman, P. and Kenworthy, M.: 1990, *Cities and Automobile Dependence* London, Gower.

Oum, T.H., Waters, W.G. II and Jong Say Yong: 1990, *A Survey of Recent Estimates of Price Elasticities of Demand for Transport*, Policy, Planning and Research Working Paper WPS 359, Washington DC, World Bank.

Park, S.-H., Dissmann, B., Nam, K-Y.:1993, 'A Cross-Country Decomposition Analysis of Manufacturing Energy Consumption', *Energy* **18**, 843-858.

Phylipsen, G.J.M., Blok, K. and Worrell, E.: 1997, 'International Comparisons of Energy Efficiency: *Energy Policy* **25**(7-8), .715-725.

RIVM: 1998, IMAGE 2.2 Data, provided by Marco Janssen and Bert de Vries, Bilthoven, The Netherlands, RIVM.

Ross, M.H. and Steinmeyer, D.: 1990, 'Energy for Industry', *Scientific American* **263**, 89-98.

Sathaye, J. and Ketoff, A.: 1991, 'CO_2 Emissions from Major Developing Countries: Better Understanding the Role of Energy in the Long Term,' *The Energy Journal*, **12**(1): 161-196.

Sathaye, J., Ketoff, A., Schipper, L., and Lele, S.: 1989, *An End-Use Approach to Development of Long-Term Energy Demand Scenarios for Developing Countries*, Berkeley, CA, LBNL (LBL-25611).

Sathaye, J., Ghirardi, A., and Schipper, L.: 1987, 'Energy Demand in Developing Countries: A Sectoral Analysis of Recent Trends,' *Annual Review of Energy* **12**, 253-81.

Schipper, L.J.: 1996, Personal communication: Excel spreadsheets containing transport energy data, PASSUM.XLS and FRTSUM.XLS, versions of 9 February 1996, Paris, IEA/Berkeley, CA, LBNL.

Schipper, L. and Meyers, S.: 1992, *Energy Efficiency and Human Activity: Past Trends, Future Prospects,* New York, Cambridge University Press.

Schipper, L.J. and Tax, W.: 1994: 'Yet Another Gap?' *Transport Policy*' (1):1-20.

Schipper, L., Figueroa, M.J., Price, L. and Epsey, M.: 1993, 'Mind the Gap: the Vicious Circle of Measuring Automobile Fuel Use', *Energy Policy,* 1173-1190.

Schipper, L., Hass, R., and Sheinbaum, C.: 1996, 'Recent Trends in Residential Energy Use in OECD Countries and Their Impact on Carbon Dioxide Emissions: A Comparative Analysis of the Period 1973-1992,' *Journal of Mitigation and Adaptation Strategies for Global Change* **1**, 167-196.

Schipper, L., Ting, M., Khrushch, M., and Golove, W.: 1997a, 'The Evolution of Carbon Dioxide Emissions from Energy Use in Industrialized Countries: an End-Use Analysis' *Energy Policy* **25**(7-9), 651-672.

Schipper, L., Scholl, L., and Price, L.: 1997b, 'Energy Use and Carbon Emissions from Freight in 10 Industrialized Countries: An Analysis of Trends from 1973 to 1992', Transportation Research-D, **2**(1), 57-76.

Segal, R.: 1995, 'Forecasting the Market for Electric Vehicles in California Using Conjoint Analysis', *The Energy Journal* **16**(3), 89-111.

Sheinbaum, C. and Rodriguez, L.: 1997, 'Recent Trends in Mexican Industrial Energy Use and their Impact on *Energy Policy* **25**(7-9), 825-831.

Siddiqi, T.A.: 1994, 'Implications for Energy and Climate-Change Policies of Using Purchasing-Power-Parity- *Energy: The International Journal* **19**(9): 975-981.

Sinton, J.E., ed.: 1996, *China Energy Databook*. Berkeley, CA: LBNL (LBNL-32822 Rev. 4).

Sinton, J.E. and Levine, M.D.: 1994, 'Changing Energy Intensity in Chinese Industry', *Energy Policy* **21,** 239-255.

State Statistical Bureau of China: 1996, *China Statistical Yearbook 1996*, Beijing, State Statistical Bureau.

Szargut, J. and Morris, D.R.: 1987, 'Cummulative Exergy Consumption and Cumulative Degree of Perfection in Chemical Processes', *Energy Research* **11**, 245-261.

Torvanger, A.: 1991, 'Manufacturing Sector Carbon Dioxide Emissions in Nine OECD Countries, 1973-87', *Energy Economics* **13**(3), 168-186.

Turiel, I., Hakim, S. and Fridley, D.: 1998, 'Preliminary Results from a Bottom-Up Analysis to Determine Residential Energy Consumption in the Emerging Economies of the World', *Proceedings of the 1998 American Council for an Energy Efficient Economy Summer Study on Energy Efficiency in Buildings*, Washington, D.C., ACEEE.

UN: 1996, *World Population Prospects*: *1996 Revision*. New York, U.N.

U.S. Congress, OTA: 1992, *Building Energy Efficiency*, Washington, DC, U.S. Government Printing Office (OTA-E-518).

U.S. Congress, OTA: 1993, *Energy Efficiency Technologies for Central and Eastern Europe*, Washington, DC, U.S. Government Printing Office (OTA-E-562).

U.S. DOE: 1995, *Effects of Feebates on Vehicle Fuel Economy, Carbon Dioxide Emissions, and Consumer Surplus, Energy Efficiency in the U.S. Economy, Technical Report Two* DOE/PO-0031, Washington, DC, U.S. DOE.

U.S. DOE, Energy Information Administration: 1992, *Commercial Buildings Energy Consumption Survey: Commercial Buildings Energy Consumption and Expenditures 1989*, Washington, DC, U.S. DOE (DOE/EIA-0318(89)).

U.S. DOE, Energy Information Administration: 1994, *Commercial Buildings Energy Consumption Survey: Commercial Buildings Energy Consumption and Expenditures 1992*, Washington, DC, U.S. DOE (DOE/EIA-0318(92)).

Van Vuren, D.: 1995, 'Modelling Metal Resource Use', M.Sc. Thesis, Utrecht, The Netherlands, Department of Science, Technology & Society, Utrecht University.

Vouyoukas, L.: 1993, *Elasticities for OECD Aggregate Final Energy Demand*, Paris, IEA.

Wall, G.: 1988, 'Exergy Flows in Industrial Processes', *Energy* **13**, 197-208.

Walls, M.A., Krupnick, A.J. and Hood, H.C.: 1993, *Estimating the Demand for Vehicle-Miles-Travelled Using Household Survey Data: Results from the 1990 Nationwide Personal Transportation Survey*, Resources for the Future discussion paper ENR 93-25, Washington, DC, Resources for the Future.

Walsh, M.P.: 1993, 'Highway Vehicle Activity Trends and Their Implications for Global Warming: the United *Transportation and Global Climate Change.* [D.L. Greene and D.J. Santini (eds.)], Washington, DC, American Council for an Energy-Efficient Economy.

Williams, R.H., Larson, E.D., and Ross, M.H.: 1987, ‘Materials, Affluence, and Industrial Energy Use’, *Ann. Rev. Energy* **12**, 99-144.

Wödlinger, R., Neubauer, H. and Baumgartner, K.: 1997, ‘Weltweite Angebots-und Nachfragesituation nach Stahl soie nach Rohstoffen und Energieträgern’ *Berg-und Hüttenmännische Monatshefte* **142**(7), 284-292.

World Bank: 1995, *World Data 1995: World Bank Indicators on CD-Rom,* Washington, DC: The World Bank, International Bank for Reconstruction and Development

WEC: 1995a, *Energy Efficiency Utilizing High Technology: An Assessment of Energy Use in Industry and Buildings*, Prepared by M.D. Levine, E. Worrell, N. Martin, L. Price, London, WEC.

WEC: 1995b, *Global Transport Sector Energy Demand Towards 2020*, Project 3, Working Group D. London, WEC.

Worrell, E., Levine, M.D., Price, L.K., Martin, N.C., van den Broek, R., and Blok, K.: 1997a, *Potential and Policy Implications of Energy and Material Efficiency Improvement*, New York, UN, Commission for Sustainable Development.

Worrell, E., Price, L., Martin, N., Farla, J., and Schaeffer, R.: 1997b, ‘Energy Intensity in the Iron and Steel Industry: A Comparison of Physical and Economic Indicators’, *Energy Policy* **25** (7-8), 727-744.